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Industry

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EXECUTIVE SUMMARY

This chapter provides a summary of options for reducing greenhouse gas emissions from industry, based on a survey of relevant literature. The main purposes are to outline the major sources and trends of emissions from industrial activity and to indicate possible abatement strategies from technological and institutional viewpoints. Emissions from power-generating utilities are not covered; the reader is referred to Chapter 19 for a discussion of this subject. Cogeneration emissions are included in this chapter only to the extent that they take place within an industry. The main findings and conclusions of the chapter follow:

- Industrial sources contribute to greenhouse gas (GHG) emissions in two major ways—fossil fuel combustion for energy and process-related emissions.
- The industrial sector is responsible for more than one-third of global carbon dioxide (CO_2) emissions through energy use. Based on current energy-use patterns, global energy use is expected to rise 75% by the year 2025, with an increasing portion of growth expected to occur in developing countries.
- Several technologies, processes, and new product design concepts exist that could substantially reduce GHG emissions:
  - For industrialized countries, reducing the material content of products, improving energy efficiency, and using fuels with a lower carbon content are essential to lower CO_2 emissions from the industrial sector.
  - For the reindustrializing, transitional countries of eastern and central Europe, as well as the world's developing countries, seizing the opportunity to shift to more advanced technologies will place these countries on a much lower GHG development trajectory.
- Technology transfer from industrial to industrializing countries and the establishment of innovative capacity building in developing countries are expected to generate lower GHG emissions.

Industry Emissions of Greenhouse Gases

Industrial sources of greenhouse gases are related to industrial energy use and to specific industrial production processes. The major industrial trends influencing the growth of future industry-related CO_2 emissions are the aggregate growth rate of industrial output; the structure of industrial growth (in particular the relative share of the energy-intensive, materials-producing subsector); the average energy intensity of specific products; and the fuel mix used in industry. The major challenge for future reductions in the period 1990–2020 is in the area of CO_2 from fossil fuels.

Examples of the historic correlation between growth in per capita gross domestic product (GDP) and fossil fuel CO_2 are examined for several industrialized and developing countries. The industrial-sector contribution of CO_2 varies greatly among countries. The consequences of different technological choices and strategies to date demonstrate that different industrial development paths—with substantially lower greenhouse gas emissions—are possible.

Regarding specific industry emissions, energy-intensive industries such as chemicals, cement, and steel have shown substantial improvements in energy efficiency during the past 20 years, albeit unevenly in different countries. The switch to less carbon-intensive fuels also has continued, so that CO_2 decreases have occurred in some industries during this period. The wood and paper industries in industrialized countries have reduced fossil fuel carbon emissions dramatically by using waste biomass in efficient cogeneration systems. In newly industrializing economies, efficiency gains have been slower because of a lack of economic resources and access to newer technologies. Some industrial processes are beginning to approach thermodynamic energy-efficiency limits; future gains will have to come from materials substitution, process changes, energy supply shifts, and alternative resource and industrial strategies.

Traditional emissions accounting has included all CO_2 emissions from fossil fuels as though they were part of the energy sector. In steel, aluminium, hydrogen, and ammonia production, much of the carbon release actually is process related and could be eliminated by changing production processes. Controlling process-related greenhouse gases, such as halocarbons and hydrohalocarbons, also is important, given their large greenhouse warming potential and long atmospheric lifetimes. Finally, altering chemical manufacturing processes can reduce nitrous oxide (N_2O).

Technical Abatement Options

Different strategies for reducing greenhouse gas emissions deserve attention, particularly fuel substitution—with increased use of lower-carbon fuels, biomass, and renewable energies in industrial processing—and efficiency improvement of energy supply (e.g., cogeneration) and energy use in industrial processes, including less materials-intensive production methods and renewable feedstocks and raw materials. Implementation would be most cost-effective during normal capital stock turnover.

Industries often have high energy-consumption levels, with large amounts of waste heat being released to bodies of water or the atmosphere. Heat cascading can be incorporated into a new or existing factory if careful attention is paid to the temperatures of its various industrial processes. Waste-heat recovery, which usually is aimed at rationalizing specific industrial processes, can be more effective at the level of coordinated manufacturing and energy industrial complexes. Further improvements could involve integrating energy-use issues into urban infrastructure from the initial stages of city planning with the development of support systems such as thermal-management technologies, regulations, and social mechanisms.

The manufacturing sector uses materials and chemicals to generate production and consumption goods, which ultimately are discarded or recycled. Recycling can involve restoring the material to its original use or “cascading” the material by successively downgrading its use into applications requiring lower quality. Materials cascading is well-established in the paper industry, for example, and is effective when recycling products back into the same ones is too energy-intensive or difficult. Generating materials from scrap tends to produce fewer GHGs and is less expensive than the use of primary raw materials, but there may not always be markets for downgraded materials. Emphasis also is needed on technological innovation to upgrade the quality of recycled products.

Analysis of opportunities and priorities entails preventive environmental management based on environmental, material, energy, health, and safety audits. Life-cycle analyses of energy and material flows and costs from an industrial ecosystem perspective also are essential to implement adequate solutions. Industrial systems that efficiently use waste materials and energy could produce major reductions in GHGs. Structural economic changes also are needed, as is a greater emphasis on choosing inherently lower-emitting technologies, designing products for greater reuse and recycling potential, and the replacement of nonrenewable resources with a biologically renewable resource base.

Implementation Aspects

Implementation problems to improve energy and material efficiency in industry may involve information and training aspects, financial and economic conditions, or legal and institutional issues. In the case of industrialized countries, efficiency improvements become more difficult when world energy prices are low. Imposition of ecotaxes to stimulate efficiency in industry is a complex issue because taxes that are not levied on a global scale may provoke industry relocation, which may in turn have adverse effects on emissions efficiency. Systems of internationally traded emission permits and opportunities for joint implementation are other alternatives that require careful consideration, given their economic and political implications.

In developing countries, raising efficiency levels involves complex factors such as the higher capital and foreign-exchange requirements usually associated with more-efficient processes. Moreover, the scale of operations, the scarcity of management resources, and the age composition of equipment creates additional difficulties that are not easily overcome from a purely energy-oriented point of view. Although technology transfer programs could potentially assist in the early adoption of efficient equipment, there is no reason to be more optimistic about their success in the case of energy technology than in the case of other technologies. In all countries, the tendency to look exclusively at short-term financial and economic factors to determine efficiency improvement potential overlooks institutional and organizational issues that are equally important in realizing those potentials. This is particularly true of improvements in materials efficiency, where institutional arrangements for collecting and recycling materials are crucial for a proper functioning of markets.

20.1. Introduction

A range of industrial activities and the use of manufactured products contribute significantly to the buildup of greenhouse gases (GHGs) in the atmosphere. Therefore, any attempt to slow the release of greenhouse gases will require a major restructuring of existing development patterns. The challenge is to determine if existing and future needs (and wants) for goods and services can be met without adversely altering the composition of the atmosphere and the planet's climate system.

The major contribution of greenhouse gases by the industrial sector is from carbon dioxide (CO_2) released by the burning of fossil fuels for energy. In addition, the industrial sector is responsible for significant releases of process-related greenhouse gases, including CO_2, methane (CH_4), nitrous oxide (N_2O), and other industrial gases, of which the most prominent are halocarbons and hydrohalocarbons. Sulfur oxide emissions associated with energy use and from the smelting of sulfide ores appear to be responsible for some cooling as well as for regional environmental damage.

Technological mitigation options for greenhouse gases are increasingly being sought so that societies can continue meeting human needs without jeopardizing the global climate system. This effort must be part of a comprehensive reexamination of industrial activity to address a full range of environmental and economic issues in the context of industrial ecology (i.e., meeting development goals within local and global sustainability capacities). Industrial ecology approaches attempt to emulate natural systems by utilizing waste from one industrial process as feedstock for another; efficiently utilizing "waste heat"; designing industrial processes to minimize energy and materials use; and replacing hazardous substances with more environmentally benign substitutes. Several recent works describe the industrial ecology approach and cite examples of recent attempts to implement it (Socolow *et al*., 1994; Ayres and Simonis, 1994; Allenby and Richards, 1994).

This chapter attempts to identify existing and possible future technologies and industrial processes that can be adopted by industrial societies—which now produce the majority of greenhouse gases—by transitional economies, and by developing countries where emissions are increasing as efforts are made to improve the standard of living and material well-being of citizens. Technology transfer from industrial countries to industrializing nations and the establishment of innovative capacity-building in developing countries in accordance with the principles of Agenda 21 (UN Conference on Environment and Development, Rio de Janeiro, Brazil, 1992) are essential if the unwanted global consequences of increased atmospheric concentrations of greenhouse gases, sulfate aerosols, and climate change are to be avoided.

20.2. Industrial-Sector Emissions of Greenhouse Gases

20.2.1. Industrial Energy from Fossil Fuels

In 1990, the world industrial sector consumed an estimated 98 EJ of end-use energy (including biomass) and 19 EJ of feedstocks to produce \$6.7 x 10^{12} of value added. This consumption resulted in the direct release of an estimated 1,200 Mt C. Electricity and cogenerated process heat added an additional 883 Mt C, for a total industrial-sector contribution of 2,083 Mt C—more than one-third of the total (Grubler and Messner, 1993).

Because countries differ significantly in their methods for recording and maintaining energy and economic data, precise comparisons are not always possible. The industrial use of energy for manufacturing, mining, construction, and feedstocks in Organisation for Economic Cooperation and Development (OECD) countries has fluctuated around 40 EJ since 1970 and typically is only 25–30% of total energy use. Developing countries are estimated to have raised their industrial energy use to 30 EJ by 1988 (35–45% of total energy); the transitional Eastern and Central European economies peaked at around 28 EJ of industrial energy in 1988, but experienced estimated declines of as much as 12% in the next 3 years. The industrial fraction of energy use by the Soviet Union was approximately 40% and that of China 60% in 1988 (Schipper and Meyers, 1992). In part, this variation reflects not only differences in energy intensity but also the more-rapid growth of the industrial sectors of developing countries, the restructuring of OECD economies from manufacturing to service, improved energy efficiency in manufacturing, and the transfer of some energy-intensive industries to developing countries. Within this context, attention should be paid to the potential danger of transferring greenhouse gas-intensive, ecologically damaging processes and production of chlorofluorocarbons (CFCs) to transitional and developing countries.

Worldwide future trends of industrial energy have been projected by inputting data from the Energy Modeling Forum report (EMF, 1994) into the Asian Pacific Integrated Model (AIM) (Morita *et al.,* 1994; Matsuoka *et al.,* 1994). These projections indicate that worldwide industrial energy use could rise from about 107 EJ/yr in 1990 to 140 and 190 EJ/yr in 2025 and 2100, respectively, if emissions are stabilized. These figures would increase to yearly consumption of 242 EJ in 2025 and 500 EJ in 2100 if based on an accelerated-technology scenario (EMF, 1994), where it is assumed that 400 EJ/yr of low-cost biomass becomes available in 2020; 20% of this resource is available at \$1.40/EJ and the remaining 80% at \$2.40/EJ.

The energy sector as a whole is thought to contribute about 57% of global warming (IPCC, 1990). Energy use in the industrial sector varies vastly among different countries. An examination of data sets that attempt to disaggregate the energy use of particular economies reveals that the structure of economies and the availability of particular energy sources play major roles in the contribution of greenhouse gases by the industrial sector. A summary of energy-related CO_2 releases for the industrial sectors of the 15 largest CO_2-emitting countries is presented in Table 20-1 (di Primio, 1993).

Clearly, improving the energy efficiency of industrial processes can substantially lower the release of fossil-fuel carbon dioxide; subsequent examples illustrate the potential for substantial

Table 20-1: Fossil-fuel carbon dioxide from the 15 largest emitters.[1]

	Total C Emissions (Mt C)	Industrial C Emissions (Mt C)	Industrial % of Total
United States	1394.83	275.4	19.74
USSR[2]	960.76	295.94	30.80
China[3]	519.25	234.29	45.12
Japan	280.40	70.78	25.24
Former West Germany	189.19	31.78	16.80
United Kingdom	154.95	21.36	13.78
India[4]	130.45	37.71	28.90
Poland[2]	126.27	15.60	12.36
Canada	122.00	27.11	22.22
Italy	108.28	20.94	19.34
France	103.72	21.05	20.29
East Germany[2]	88.69	8.87	10.01
South Africa[2]	88.31	18.27	20.69
Mexico[2]	74.17	17.62	23.75
Czechoslovakia[2]	65.63	17.75	27.05

[1]Values are for 1990, unless otherwise noted. Feedstocks are not included in either total carbon data or industrial carbon data; values for electricity inputs into the industrial sector are not included (di Primio, 1993).
[2]1988 (represents latest available data).
[3]1985 (represents latest available data).
[4]1987 (represents latest available data).

reductions. Ultimately, however, thermodynamic free-energy limits preclude further reductions. Any additional lowering of industrial energy emissions can come only by shifting from fossil fuels to non-carbon-based energy sources—such as hydro, nuclear, wind, solar, and geothermal—or by using biomass.

In terms of absolute contribution to global-warming potential, the major sources are CO_2 from fossil-fuel combustion and halocarbons. Cement calcination is the third most important source. Estimates of the quantities of global-warming potential in terms of gigatons of carbon equivalent for these three sources in industrialized, transitional, and developing countries are presented in Table 20-2. It appears that these industrial sources account for close to 30% of total global-warming potential.

20.2.2. Industrial Processes as Sources of Greenhouse Gases

In addition to the release of energy-related greenhouse gases, the industrial sector is responsible for the release of a number of process-related greenhouse gases—although estimates of these gases vary in their reliability. They include halocarbons and hydrohalocarbons, CO_2, CH_4, and N_2O. Whereas CO_2 emissions from fossil-fuel combustion represent the largest portion of industry greenhouse gases, the contribution of process-related emissions other than halocarbons is less recognized. Changing the production process has the potential to eliminate all greenhouse gases associated with a particular industrial or manufacturing operation. For the United States, process CO_2 emissions in 1991 are estimated to have amounted to 15.6 Mt C (EIA, 1993), or 1.2% of total fossil-fuel releases. In the comprehensive Oak Ridge data set, non-fuel-related CO_2 is estimated explicitly for cement making and implicitly from coal, natural gas, and petroleum that is oxidized in the manufacturing process (Marland, 1994; IPCC, 1991). Examples of process-related GHG releases are presented in Table 20-3; they are discussed under the appropriate industry group in Section 20.3. In some cases—such as the production of cement, lime, and iron—the release of greenhouse gases is intrinsic to the product, so the only option for GHG reductions is material substitution.

Industrial process-related gases include the following:

- CO_2 from the production of lime and cement (calcination process), steel (coke and pig-iron production), aluminum (oxidation of electrodes), hydrogen (refineries and the chemical industry), and ammonia (fertilizers and chemicals)
- Halocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) produced as solvents, aerosol propellants, refrigerants, and foam expanders
- CH_4 from miscellaneous industrial processes (iron and steel, oil refining, ammonia, and hydrogen)
- N_2O from nitric acid and adipic acid (nylon) production
- Carbon tetrafluoride or CFC-14 (CF_4) and hexafluoroethylene or CFC-116 (C_2F_6) from aluminum production (electrolysis).

Estimates of the contribution from other minor sources vary considerably. For CH_4 leakages in industrial processes and industrial-fuel combustion, a range of 1–3 Mt of CH_4 for combustion and 3–20 Mt of CH_4 for processing is reported in the literature, reflecting large uncertainties (Berdowski, 1993). Total global anthropogenic emissions amount to roughly 360 Mt of

Table 20-2: Contribution of industry to global GHG emissions (Gt C-1990).

	Fossil Fuels[1]	Halo-carbons	Cement Production[2]	Total
Industrial Economies	0.72	0.85	0.04	1.61
Transitional Economies	0.48	0.22	0.02	0.72
Developing Economies	0.68	0.22	0.07	0.97
Total	**1.88**	**1.29**	**0.13**	**3.30**

[1]Final demand.
[2]Process emissions.

Table 20-3: *Industrial process-related greenhouse gases.*

Industrial Process	**Halocarbon/ Hydrohalocarbon**	**CO_2**	**CH_4**	**N_2O**
Solvents	✔			
Refrigerants	✔			
Foam Blowing	✔			
Cement		✔		
Ammonia		✔	✔	
Hydrogen		✔	✔	
Nitric Acid				✔
Nylon				✔
Aluminum	✔	✔		
Steel		✔	✔	

CH_4. Estimates of industrial N_2O leakages in nitric acid and nylon production (adipic acid) are equally uncertain but now are considered more important than originally thought. A range of 0.5–0.9 Mt of nitrogen—20 to 50% of total anthropogenic N_2O emissions—is mentioned in the literature (Olivier, 1993). Abatement technologies are available that employ conversion to recoverable nitrogen dioxide (NO_2), catalytic dissociation into molecular nitrogen (N_2) and molecular oxygen (O_2), or improved N_2O destruction in specially designed boilers.

Halocarbons not only cause higher radiative forcing, they also deplete stratospheric ozone. Reduction of many halocarbons, including CFCs, already is occurring in industrial and a few developing countries because of the Montreal Protocol and subsequent amendments. The contribution of halocarbons to radiative forcing will begin to decrease after 2000, although concern over illegal imports into industrial countries is growing (*Scientific American*, 1995). Hydrohalocarbon substitutes for CFCs are expected to grow rapidly in the coming decades and will make modest additions to total warming potential.

20.2.3. Past Trends and Future Prospects for Industrial-Sector GHG Emissions

To discuss the historical and future trends in GHG emissions from industrial energy use, it is convenient to distinguish four essential driving forces. The impact of each driving force on GHG emissions can be influenced by specific policies. These four driving forces and their respective policy domains follow:

- Growth in the volume of industrial production (volume effect—macroeconomic policies), which indicates the quantitative impact of industrial growth
- Changes in the sectoral pattern of industrial growth (structural effect—sectoral policies), which indicate the qualitative impact of industrial growth
- Reduction in energy use for specific products (efficiency effect—energy conservation policies), which is a measure of the impact of energy efficiency improvements
- Changes in energy carrier composition (fuel-mix effect—energy supply policies), which indicate the potential to replace coal and oil by natural gas, renewables, or nuclear energy.

To discuss actual trends and policy opportunities with respect to these four driving forces, it is convenient to distinguish between three regional groups of countries: industrial economies (OECD), transitional economies (Eastern Europe and the former Soviet Union), and developing economies (the rest of the world). The discussion centers on manufacturing, which generally accounts for more than 90% of industrial energy demand. Data on other industrial sectors (energy and mining) are not included.

20.2.3.1. Trends for Industrialized (OECD) Countries

Average manufacturing value in industrialized nations grew from 1973 to 1988 at about 2.3% annually. Nevertheless, energy use decreased by about 1.2% annually. Aggregate manufacturing energy intensity was substantially reduced: in Japan by 45%, in the United States by 43%, and in Europe by 34%. Energy intensities for specific industries in the United States tend be higher than those in European countries, whereas those in Japan tend to be lower.

Schipper and Myers (1992) examined the energy/economic value ratio for a variety of industrial sectors for the United States, Japan, and six European countries. All major industrial sectors recorded gains in measured energy efficiency between 1971 and 1988. For this group of eight nations, energy intensity for chemicals declined by 37%, pulp and paper by 27%, building materials by 32%, ferrous metals by 27%, and nonferrous metals by 26%. Surprisingly, less energy-intensive sectors also declined by an average of 37% during the same period. Ferrous metals and pulp and paper require the greatest energy per value added, followed by nonferrous metals, building materials, and chemicals. The major source of these gains was identified as a combination of 1) better housekeeping practices in operation and maintenance, 2) higher cost investments in process equipment, and 3) replacement of older, less efficient technology with new production processes. In some subsectors such as chemicals, there is also some shift to less energy-intensive products. An excellent case study of how multimillion dollar energy efficiency gains have been achieved in the American chemical industry has been given by Nelson (1994).

Several groups have attempted to assess the potential for future savings from energy efficiency gains in the industrial sector of specific economies. The analysis carried out for the Swedish utility Vattenfall identified major industrial energy savings that would lower CO_2 significantly by 2010 (Johansson *et al*., 1989).

Statistical analysis of the impact of changes in the sectoral composition of industrial production on energy demand show that in this period structural change generally had a continuous, but relatively small, effect in reducing energy demand. Efficiency

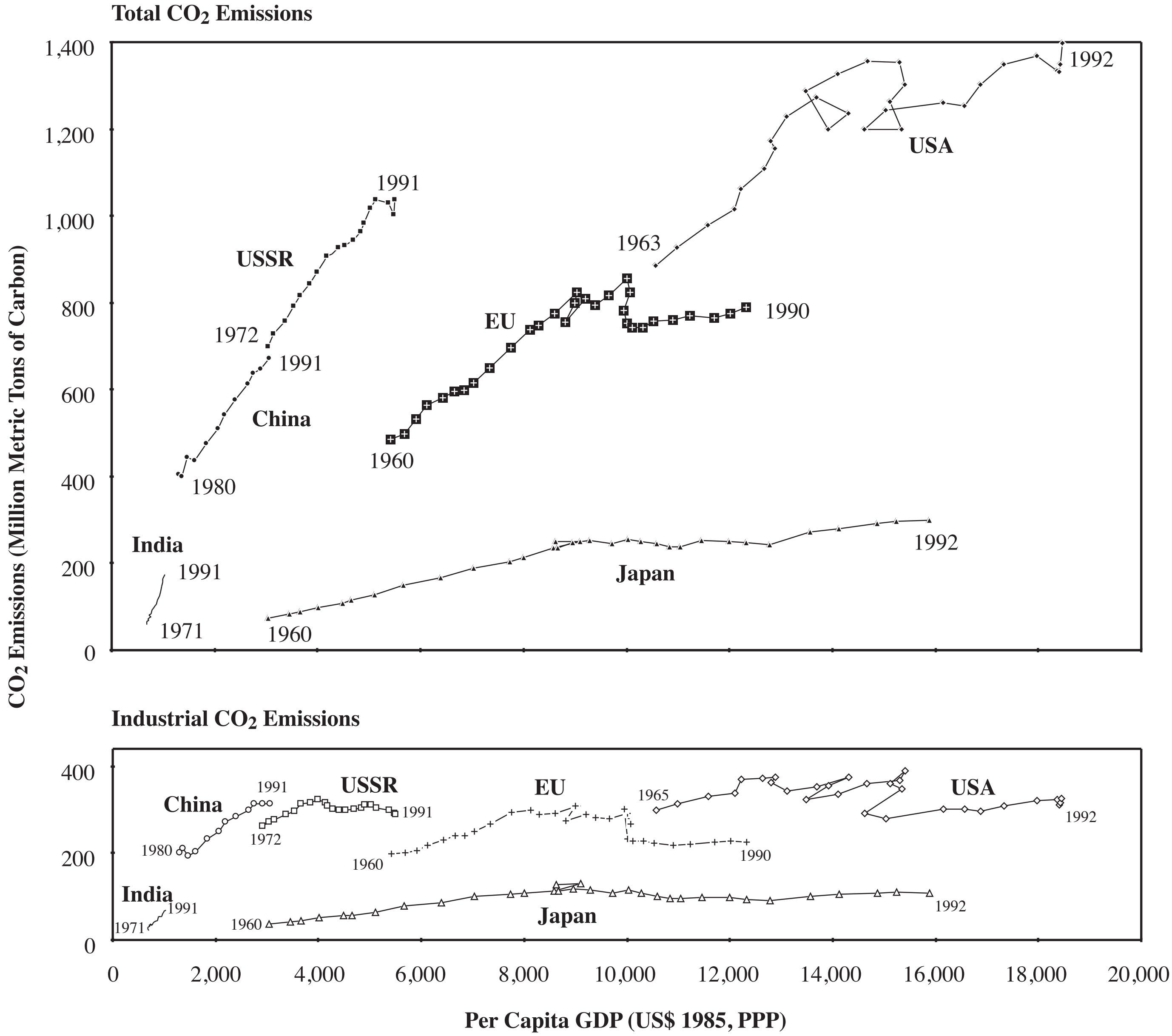


Figure 20-1: Fossil fuel CO_2 development path for the total economy (upper panel) and the industrial sectors (lower panel) of the United States, the 15 nations that now comprise the European Union (less East Germany), Japan, China, India, and the former Soviet Union. The industrial sector is as defined by OECD, plus CO_2 associated with refineries and the fraction of electricity that is used by industry. The CO_2 values are from OECD (1994) and the purchasing power parity (PPP) values are from Summers and Heston (1991, 1994).

improvements have been much more important than structural changes in curtailing energy demand, particularly in the period after 1980 when energy prices were very high (Bending, 1987; Schipper, 1992). Cyclical movements complicate this picture considerably because energy-intensive industries, such as the metallurgical and chemical subsectors, are much more sensitive to business cycles than is aggregate industrial production. Moreover, historical trends are different for fuels and electricity. In general, net improvements in electricity efficiency have been lower than in fuel-use efficiency because of the relatively important role of new electricity-using technologies in manufacturing, which offsets efficiency gains in traditional electrical equipment. Given these energy-demand trends and taking into account the industrial fuel-composition changes toward natural gas, the general trend for GHG emissions from fuel combustion in the manufacturing sector of industrial nations in the past 2 decades has been downward (Torvanger, 1991; Figure 20-1). The overall decrease from 1973 to 1991 was about 15%.

Under business-as-usual conditions, emissions from industrial countries will continue to grow moderately but with a gradual shift away from energy-intensive industries. The materials-producing industries are likely to have slower growth than less energy-intensive industries. This trend is caused partially by saturation effects on the materials demand side (Williams, 1987) and partially by ongoing economic globalization, which may shift energy-intensive industries to countries with major natural resource endowments (e.g., minerals, fossil fuels, and hydropower) and lower environmental priorities (because of lower environmental loads and urgent poverty problems). Nevertheless, the continuing improvement of bulk transportation technology and the growing integration of quantity-oriented production of bulk materials with quality-oriented production of semifinished products may put a substantial brake on the latter trend. Opportunities for further energy conservation are certainly available, especially for newly emerging industries. Fuel-mix effects may tend to increase emissions by a modest amount because the share of coal may increase after the year 2000. The aggregate impact of all effects leads more or less to a stabilization of GHG emissions in OECD industrial countries.

20.2.3.2. Trends for Transitional Economies

Whereas many studies analyze industrial energy demand developments in OECD countries, the historical evidence regarding transitional economies is much scarcer. Data availability and compatibility problems abound. In transitional economies, industry has been very dominant, accounting for approximately half of total energy use. Through the late 1980s, energy demand grew at a rate of about 2% annually, with relatively little progress in energy efficiency or structural change. In the 5 years after it reached a peak in 1988, industrial energy demand dropped sharply from central planning levels, although less so than industrial output. CO_2 is estimated to have dropped by a little more than 25% in the former Eastern bloc between 1988 and 1993 (Brown *et al*., 1995). Thus, manufacturing energy demand and related GHG emissions have been much more directly coupled to aggregate industrial growth and decline (volume effects) and much less affected by structural and efficiency effects than has been the case in OECD industrialized nations. The trend for transitional economies with respect to GHG emissions had been strongly upward until 1989; at that time, a clear break occurred, and the trend has been sharply downward to the present.

For transitional economies, the rate of economic activity is likely to be more fluctuating than for OECD countries. In the short run, a further decrease in aggregate industrial energy demand can be expected because of the ongoing, dramatic restructuring of the industrial sector—which may affect the energy-inefficient heavy industries in particular. Although some Eastern European countries already are recovering from earlier transition difficulties, this is not yet the case for the former Soviet Union, where further declines are expected (Schipper and Martinot, 1993). At least for the period 1990 to 1995, a sharp drop in GHG emissions is fairly certain. Nevertheless, in the long run, these economies may expand again at a high rate, compensating for their earlier performance lapses. By that time, the relatively strong role of heavy industry will not continue under conditions of a market economy, and the development of the sectoral pattern will be toward reduced GHG emissions. Given excessively high current energy intensities, opportunities for energy conservation are very great. Finally, because of the increasing role of natural gas, the fuel mix is likely to change in a direction favorable for reducing GHG emissions, provided that the high leakage rate of the gas transmission and distribution system can be addressed. The aggregate impact of all effects probably will lead to a small decline in industrial GHG emissions between 1990 and 2020.

20.2.3.3. Trends for Developing Countries

Industrial energy use in developing countries is dominated by China, India, and Brazil. Until 1980, China followed national policies focusing on heavy industry; since 1980, however, the emphasis has shifted toward lighter industries. Industrial growth has been very high—14% annually. At the same time, aggregate manufacturing energy intensity declined considerably—30% between 1980 and 1988 (Huang, 1993). However, structural change accounted for only a small part of this reduction; most of the change was caused by efficiency improvements in all industrial sectors. Industrial growth in India has been slower in the same period but still impressive, at roughly 7% annually. India's energy efficiency increased by about 25%. A larger part of this improvement probably was accounted for by structural changes than was the case in China. The picture for Brazil is altogether different because the growth in export-oriented, energy-intensive industries was very high. From 1973 to 1988, industrial production increased by 65% while energy intensity increased by 25%, leading to a doubling of total energy use. Structural changes between and within industrial sectors were the dominating force, more than compensating for efficiency improvements in individual sectors (Keller, 1991). However, part of this growth has been based on hydroelectric developments and, because of the effects of shifts to biomass alcohol fuel, the additions to GHG emissions are less than energy demand growth.

A study of the Indian industrial sector concluded that energy efficiency gains of 8–10% were possible in the metals industries; 10–15% in chemicals, ceramics, and glass; 20–25% in cement and pulp and paper; and 70–80% in sugar refining. These gains would bring Indian industrial energy intensity more into line with energy-efficient modes of production (TERI, 1991).

With respect to other developing countries, few general conclusions are possible—given the widely diverging industrial developments of Southeast Asian economies versus sub-Saharan economies, for example. The developing world as a whole is experiencing an upward and accelerating trend in industrial GHG emissions.

The largest single additive impact in all respects will come from industrial growth in developing countries. Moreover, because the world's most populous countries—China and India—are dependent to a large extent on domestic coal resources, this impact will be reinforced by an additive fuel-mix impact through increased average CO_2 content of industrial energy use. The impact from sectoral shifts (qualitative structural change) will be additive but relatively small because major expansions in the bulk-materials industries already have taken place. Although the potential for reductions in specific energy use are large, they are likely to meet severe implementation problems, and they will be insufficient to counteract the other effects in a major way. The aggregate effect will lead to a relatively rapid increase in GHG emissions.

20.2.4. Variations Among Regional Groups

It is important to stress that not all economies produce the same levels of greenhouse gases even when they have achieved the same average levels of affluence. An examination of these differences among countries and the particular economic development paths they have followed in getting to their present economic and industrial stage of development can provide useful insights into which policies and strategies may be most effective for producing lower-GHG industrial societies. Figure 20-1 illustrates fossil fuel development paths over the past 30 years for the United States, the 15 nations that now comprise the European Union (less East Germany), Japan, China, India, and the former Soviet Union (Moomaw and Tullis, 1995). These countries accounted for just over 80% of global CO_2 emissions in 1990. Both total and industrial-sector CO_2 emissions are correlated with national GDP, which is expressed as purchasing power parity in 1985 U.S. dollars (Summers and Heston, 1991, 1994). The industrial-sector carbon dioxide data consist of industrial-sector emissions plus refinery emissions and the industrial electricity fraction of each nation's electric power-sector emissions (OECD, 1994). It is clear that different nations have followed very different fossil-fuel trajectories to arrive at their present economic status (Moomaw and Tullis, 1994). The decline in CO_2 in the former Soviet Union is tied to the decrease in industrial output. Whereas total and industrial-sector CO_2 emissions continue to rise for expanding industrializing economies like those of China and India, they have nearly leveled off or decreased for industrial nations. It is important to note that the industrial-sector and total CO_2 emission levels of most OECD countries are below their historic peaks even though their economies and populations have continued to expand.

The expected large impact of volume growth in developing nations does not imply that they will follow the historic industrialization path of industrial nations. Technological developments have changed the optimal scale of production and production-factor requirements dramatically in the past few decades. Moreover, the availability of resources and their relative prices in developing countries are not comparable to historic conditions in industrial countries. Information technology and materials technology have changed industrial processes enormously in the recent past and will continue to do so in the near future. It may well be possible for developing countries to undergo an earlier carbon transition than was the case for present industrial nations.

20.3. Specific Industry Emissions

20.3.1. Basic Metals

The iron and steel, aluminum, copper, and other nonferrous metal industries are extremely energy-intensive (and release process CO_2 and other GHGs, as well). In the United States, they are the leading industrial producers of CO_2, at 63.1 Mt C or 20% of the industrial sector (Marland and Pippin, 1990). Significant efficiency gains have been realized during the past 20 years as new processes have been developed.

20.3.1.1. Iron and Steel

The release of CO_2 from the iron and steel industry in 15 leading industrial nations was estimated to be 151 Mt C in 1990. Carbon inputs are equally divided between energy and chemical feedstocks such as coke. Integrated, primary steel works use approximately 550 kg C per ton of crude steel, whereas electric-arc furnaces using scrap average only 128 kg C per ton of crude steel. The European and Asian steel industries each release approximately 51 Mt C, North America 47 Mt C, and South Africa 2 Mt C. Nationally, the United States leads with 42 Mt C, followed by Japan with 37 Mt C (IISI, 1993).

Iron- and steel-related carbon emissions from the 15 leading producers amount to 2.7% of total global carbon, but their iron and steel production represents only a fraction of the world's total. Several of the largest producers are heavy coal users; they use much-less-energy-efficient technology than that cited above. For example, Japan requires only 19 GJ per ton of steel and the United States 24, but the average for the former Soviet Union is 31, China 38, and India 41 (Chandler, 1985). Additional CO_2 is released in the use of blast-furnace limestone—about 1 Mt C in the United States (Forrest and Szekely, 1991)—and in the removal of CH_4 and other gaseous components from coke. Overall, contributions of the iron and steel industry to carbon emissions could be in the range of 7 to 8% of world totals.

Significant improvements in the efficiency of steelmaking have been made during the past two decades. The Japanese industry has demonstrated a 20% improvement between 1973 and 1990 (IISI, 1993; MITI, 1994). Most of the gains have come about as the result of heat-recovery technologies, although an estimated 40% of process heat is still lost. Improvements have occurred in cokemaking, continuous casting (reducing reheating requirements), and continuous annealing. Top-pressure-recovery turbines also generate electricity from furnace top-gas during iron production. The European coal and steel community is carrying out a research program that suggests that further gains can come from scrap preheating; improved coal and oxygen use; and recycling of coke-oven, blast-furnace, and converter gas (IISI, 1993).

Additional GHG reductions can result from changing iron and steel production processes. Process-related CO_2 for the 15 leading producer countries amounts to 1.3% of global carbon emissions. The most dramatic improvements have come from the adoption of electric-arc furnaces and the efficient evolution of that technology. Using scrap eliminates carbon releases associated with metal reduction, and total carbon use per ton is only about one-fourth that of an integrated facility. Problems from contamination by impurities may limit this method and suggest that the original metallurgical design of steels should consider their recycling potential. Hydrogen rather than carbon reduction of iron ores would produce a dramatic lowering of carbon emissions if inexpensive carbon-free sources such as hydro or solar electrolysis of water could be developed (IISI, 1993). In the future, carbon for steelmaking may come from used tires or organic chemical wastes rather than from coal (Corcoran, 1994; MMT, 1993).

20.3.1.2. Aluminum

The production of bauxite ore is so localized that the top ten national producers are responsible for 92% of the world total (WRI, 1994). Similarly, aluminum production of 18.194 Mt in 1991 is concentrated in the United States (4.12 Mt), the former Soviet Union (2 Mt), Canada (1.83 Mt), Australia (1.24 Mt), Brazil (1.14 Mt), China (0.86 Mt), Norway (0.83 Mt), and Germany (0.74Mt); India (0.44 Mt) and Venezuela (0.6 Mt) also are major producers (Plunkert and Sehnke, 1991). In 1991, 17.2 Mt of aluminum was consumed, 73% of it in 10 top-consuming nations—led by the United States (24%), Japan (14%), Germany (8%), the former Soviet Union (6%), China (5%), and France (4%) (WRI, 1994).

Aluminum refining from bauxite uses vast quantities of electricity and releases CO_2 whenever coal and other fossil fuels are used. An estimated 280 x 10^9 kWh (Young, 1992) was needed to produce 18 Mt of aluminum in 1990 (Plunkert and Sehnke, 1991). The efficiency of electricity use varies from a low of 13,000–15,500 kWh per ton of aluminum in much of Europe, Brazil, Japan, and the United States to a high of 18,000–20,000 kWh/t in Norway, Russia, and Canada. Aluminum from secondary scrap requires only 1,600 kWh/t (Chandler, 1985). In most market economies, hydropower—which is inexpensive and often subsidized—is used as the source of electricity, but in Australia (the leading producer of bauxite), China, India, and the former Soviet Union, coal is a principle source of electricity. Other countries, such as Brazil, Ghana, and Canada, have large hydro projects tied to aluminum production. The United States, which used 859 PJ of energy in aluminum production in 1989, draws 12.4% from hydropower, 3.5% from nuclear, 49.6% from coal, 26.5% from oil, and 8.1% from gas (Aluminum Association, 1991).

Significant improvements in energy efficiency have been realized by the aluminum industry worldwide. In the United States, efficiency gains in 1989 were estimated at 12.1% since 1972, with an additional 9.2% arising from increases in recycled scrap—for a 21.3% reduction in energy use per ton of aluminum (Aluminum Association, 1991).

CO_2 also is released as a process gas from the destructive oxidation of the carbon anode during electrolysis of bauxite ore. Carbon emissions from this source are estimated to be 0.45 kg of carbon per kg of aluminum [some of which can be as carbon monoxide (CO) (Sadoway, 1990)]—which would imply a total release of 8.2 Mt C, or 0.15% of global fossil-fuel carbon in 1991. This carbon apparently is included in existing emission totals as part of the petroleum coke from which the electrodes are made (Marland, 1994). The use of experimental non-carbon electrodes has been demonstrated (Hryn and Sadoway, 1993), and an alternative chloride-based (rather than oxide-based) process with nondissolving graphite electrodes is claimed to release no CO_2 and to be 30% more efficient (Altehnpohl, 1980).

The second class of important aluminum process GHGs are the perfluorocarbons, carbon tetrafluoride and hexafluoroethylene, which are released during electrolysis of bauxite. These gases have an exceptionally strong absorption in the infrared and an estimated lifetime in the atmosphere in excess of 10,000 years. The range of estimates for perfluorocarbons vary from 0.6 to 2.5 kg per ton of aluminum for CF_4 and from 0.06 to 0.25 for C_2F_6 (Abrahamson, 1992; U.S. DOE, 1994; Haupin, 1987). An estimated 28,000 t of CF_4 and 3,200 t of C_2F_6 were released in 1987 (Fabian *et al.*, 1987); CF_4 has been estimated to have contributed 1.7% of the global-warming potential during the 1980s (Lashof and Ahuja, 1990).

Unfortunately, no reliable estimates of total CO_2 release associated with aluminum production exist, but in the United States, the industry accounts for 1.2% of national energy demand and a similar percentage of CO_2 emissions (Aluminum Association, 1991). If this figure prevails worldwide, then aluminum would be responsible for more than 3% of global-warming potential.

20.3.1.3. Copper and Other Nonferrous Metals

In 1992, 9.3 Mt of primary copper was mined worldwide, with nearly 40% coming from Chile and the United States. In addition, 3.4 Mt of lead, 7.1 Mt of zinc, 0.9 Mt of nickel, and lesser amounts of tin and cadmium were produced (WRI, 1994). CO_2 emissions from the U.S. primary and secondary copper industry were estimated at 19 Mt C in 1987, down from 30 Mt C in 1968 (Forrest and Szekely, 1991).

For copper and other nonferrous metals, the major greenhouse gas is CO_2 associated with the energy required for smelting from ore. These metals also are associated with other emissions, such as sulfur dioxide (SO_2). Recycling of metals can greatly reduce the energy required to produce them; substantially lower the CO_2 and SO_2 associated with mining and production; and reduce other air, land, and water pollution. For toxic metals like lead and cadmium, reduced exposure to toxicity is an additional benefit. Nondissipative uses of lead, such as storage batteries, are recycled to a large extent. Large amounts of copper also are recycled, but care must be taken to ensure that impurities in recycled copper do not reduce electrical conductivity where this is important (e.g., in power-transmission lines).

20.3.2. Chemicals

The chemical industry is extremely energy-intensive because of the source of its raw materials—petroleum and natural gas—and because of the energy required to carry out chemical transformations to final products. In the United States, chemicals accounted for 60.3 Mt or 19.6% of industrial-energy CO_2 in 1985, right behind the primary-metals sector. This sector also accounted for most of the 39.4 Mt of nonfossil-fuel carbon released by the industrial sector (Marland and Pippin, 1990). Since the oil shocks of the 1970s, the chemical industry has redesigned processes, significantly reducing energy use and lowering the production of chemical wastes. For example, the Japanese petrochemical industry reports a decrease of 47% in energy per ton of product from 1976 to 1988 though little change during the succeeding 4 years (MITI, 1994). The U.S. chemical industry reduced its energy per unit of output by 21.8% between 1974 and 1992 (Chemical Manufacturers Association, 1994).

20.3.2.1. Halocarbons and Hydrohalocarbons

Halocarbons and hydrohalocarbons currently are the major greenhouse gases associated with industrial activity. These ubiquitous substances are thought to contribute substantially to direct radiative forcing, but this effect may have been largely offset by their depletion of stratospheric ozone (IPCC, 1992). Most CFCs, halons, and solvents (such as carbon tetrachloride and methyl chloroform) are being rapidly phased out to protect the ozone layer. Proposed substitutes like HCFCs and HFCs, while having less ozone-depleting potential because of their shorter atmospheric lifetimes, have considerable global-warming capability. The United States estimates that the HFCs and fluorocarbons (FCs) released in 1990 have a warming potential equivalent to 20 Mt C, but expects this to grow to 45 Mt C by 2000 (U.S. DOE, 1994).

20.3.2.2. Plastics

Plastics and most organic chemicals are derived from petroleum and natural gas. The latest estimate is very much in need of updating, but Marland and Rotty (1984) suggest that 6.7% of liquid fossil fuels are incorporated into plastics, asphalt, and lubricants that are not immediately oxidized to CO_2. Some plastic wastes and lubricants are eventually burned as fuels, but some of this carbon—perhaps one-third—is sequestered in landfills or products. Worldwide, about 1% of natural gas is used for non-ammonia feedstock (Marland and Rotty, 1984). Energy use for plastics production was about 3% of total energy in the United States in 1988 (Franklin Assoc., 1990). An advantage of using more plastics in transportation and in transported containers is their extremely light weight, although petrochemical production is very energy-intensive. Recycling polymers is advantageous from an energy perspective but is difficult because their low density, high bulk, additives, and the mixtures of plastics in the waste stream make them difficult to reprocess. Moreover, innovation in plastics is important and makes standardization difficult. Some standardization on a smaller number of resins or other policy options might help in this matter.

20.3.2.3. Hydrogen and Ammonia

Hydrogen and ammonia are extremely energy-intensive to produce, and they use CH_4 from natural gas as a feedstock. Hydrogen is stripped from CH_4, and the carbon is oxidized and released as CO and CO_2. Marland and Rotty (1984) estimate that about 2% of global natural gas is oxidized in this way. Ogden and Williams (1989) place the energy content of hydrogen production in the United States at about 2% of total energy, which would imply that 5% of natural gas currently is used for hydrogen and ammonia production plus CH_4 leaks.

In the United States, nearly 340 x 10^9 m^3 of hydrogen are used in ammonia production, 900 x 10^9 by refineries, and 25 x 10^9 for methanol production; approximately 5.7 x 10^9 m^3 are produced as merchant hydrogen and by captive users (SRI, 1994). In addition to its main production from CH_4, hydrogen also is produced as a byproduct during oil refining and the electrochemical production of chlorine, sodium hydroxide, and sodium chlorate. Currently, some of this byproduct hydrogen is flared. The current process CO_2 from hydrogen production could be eliminated by using the electrolysis of water as the hydrogen source. At the present time, off-peak hydropower represents the only low-cost electricity supply that is large enough to make a significant contribution toward replacing natural gas as the feedstock. Off-peak power from geothermal, wind, solar (Ogden and Williams, 1989), and ocean thermal energy conversion someday may also be inexpensive enough to produce hydrogen competitively from the electrolysis of water.

20.3.2.4. Other Chemicals

N_2O contributes about 6% to increased radiative forcing, has strong infrared absorption, and has a lifetime of 140 years in the atmosphere. A full understanding of its measured increase in the atmosphere is incomplete. Contributions from fossil-fuel stationary combustion have been shown to be much lower than previously believed (Lyon *et al*., 1989).

It has been estimated that adipic acid production for nylon accounts for 10% of anthropogenic global N_2O releases (Thiemens and Trogler, 1991), with 3.03 x 10^{-4} kg N_2O released per ton of adipic acid produced (Jacques, 1992). One major manufacturer announced a revised production process that reduces emissions by 98% (*Chemical Week*, 1992). The U.S. production of N_2O associated with adipic acid production has been estimated at 242,000 t, but with the introduction of controls, only 62,000 t is released (U.S. EPA, 1993). Small additional amounts are released in the oxidation of ammonia to nitric acid at a rate of 2 to 20 kg N_2O per ton of ammonia consumed. Controls have been developed and installed in some facilities (*Chemical Week*, 1992). Canada estimates that its annual emissions from this source are only 1 kt and from adipic acid production 30 kt (Jacques, 1992).

A small amount of CO_2 is released in the manufacture and use of lime and soda ash. For the United States, this is estimated to have been 3.26 and 1.14 Mt C, respectively, in 1991 (EIA, 1993).

20.3.3. Pulp and Paper

Because wood and paper are produced from plants that absorb CO_2, they can provide long-term sequestration of carbon in durable products. The major fossil-fuel inputs for paper production are in the harvest and transport of raw materials and in producing the fiber from wood chips. Evaporation of water consumes a very large proportion of the energy in pulp and papermaking. In response to higher energy prices in the 1970s and to comply with clean-air and water requirements in several countries, the paper industry developed efficient cogeneration systems to produce needed steam, hot water, and electricity by burning liquors, bark, and other wood waste. The U.S. paper industry now satisfies 56% of its energy needs by using biofuels in this way (American Forest and Paper Association, 1993). Japan improved the energy efficiency of its pulp and paper industry by 26% between 1980 and 1992 (MITI, 1994). In developing countries, such as Mexico, bagasse from sugar cane provides fiber for papermaking (Gotelli, 1993); China, Japan, and other Asian countries produce paper from rice stalks. Pulp also is used to produce cellulosic textile fibers, such as rayon.

More than 50% of the wood cut in the United States is eventually used for paper and paperboard. Current U.S. paper recycling is 25% (Europe and Japan have achieved rates of more than 50%). A doubling of this rate would reduce the amount of wood cut from U.S. forests by about 17%. Landfills, whose contents are 40% wood and paper products, would benefit similarly in the form of a 13% reduction by weight overall. Thus, paper recycling offers the potential for reducing global warming by increasing forest stands and reducing the amount of atmospheric CH_4 and CO_2 produced from landfills (Zerbe, 1990).

20.3.4. Construction Materials

The production of high-density building materials (such as concrete, glass, brick, and tile) requires high temperatures and hence releases significant quantities of CO_2 during production. Because of their high density, these materials also require large quantities of energy in their transportation.

20.3.4.1. Cement and Concrete

Cement and concrete are key components of commercial and residential construction worldwide. During the past decade, U.S. cement consumption averaged between 75 Mt/yr and 90 Mt/yr (Portland Cement Association, 1990); it is expected to rise to more than 100 Mt/yr by 1997. Worldwide, 1991 cement production reached 1.25 x 10^9 tons (U.S. Bureau of Mines, 1992). Requiring 6.1 GJ per ton of cement (see Table 20-4), cement production is one of the most energy-intensive of all industrial processes.

CO_2 is emitted during cement production in two ways. Approximately 0.75 t of CO_2 is produced per ton of cement from combustion of fossil fuels to operate the rotary kiln. The second source is calcination, in which calcium carbonate ($CaCO_3$) from limestone, chalk, or other calcium-rich materials is heated in kilns to form lime (CaO) by driving off CO_2. This process produces about 0.5 t of CO_2 per ton of cement. Thus, combining these two sources, for every ton of cement produced, 1.25 t of CO_2 is released into the atmosphere—of which 60% comes from energy inputs and 40% from calcination (Griffin, 1987). Worldwide, cement production accounted for approximately 162 Mt of C emissions in 1991, or about 2.6% of total global carbon from oxidation of fossil fuels. The United States annually produces about 9.3 Mt C from cement production, or 6% of global cement-production carbon (CDIAC, 1993).

The carbon intensity of cement is highly dependent on the fuel chosen. Cement production to date has used coal as its primary fuel. As a result, cement production is associated with especially high levels of CO_2, nitrogen oxides (NO_x), and SO_2.

Table 20-4: *Fuel use for cement production (1990).*

Fuel	GJ per Ton of Cement	Percent
Petroleum Products (diesel, gasoline, LPG)	0.06	1.1
Natural Gas	0.5	8.2
Coal and Coke	3.7	60.8
Waste Fuel[1]	0.3	4.9
Electricity[2]	1.5	24.9
Total	**6.1**	**100.0**

Source: Portland Cement Association, 1990.
[1] Waste fuel includes used motor oil, waste solvents, scrap tires, etc.
[2] Electricity figure includes primary energy used to generate electricity.

Producing 80 Mt of cement in the United States in 1992 required about 0.53 EJ, or roughly 0.6% of total U.S. energy use. In terms of its dollar value, however, cement represents only about 0.06% of the U.S. gross national product. Thus, cement production is about 10 times as energy-intensive as the U.S. economy in general. In a number of developing countries, cement production accounts for as much as two-thirds of total energy use.

Process modifications in kiln operation show potential for energy reductions. For example, newer dry-process kilns are more energy-efficient than older wet-process kilns because energy is not required to eliminate moisture. In a modern dry-process kiln, the kiln's exhaust gases are used to preheat the ingredients and drive off moisture. Such a process uses up to 50% less energy than a wet-process kiln (UBC, 1993). Significant reductions in CO_2 emissions from cement production could still be gained by energy-efficiency improvements of cement-kiln operation. Switching to fuels with lower CO_2 content (such as natural gas and agricultural wastes) also can reduce CO_2 emissions; in addition, savings from other techniques (e.g., fly-ash substitution and the use of waste fuels) are possible. Using waste lime from other industries could reduce CO_2 emissions from the calcination process.

20.3.4.2. Brick

Total brick production in the United States has varied recently between about 5 x 10^9 and 8.5 x 10^9 bricks per year. In 1992, production was about 6.25 x 10^9 units. Brick manufacturing constitutes about 96% of total clay-product manufacturing in the United States. Energy estimates for brick production vary widely. In the United States, the most-efficient brick producers, using modern computer-controlled equipment, require between 4.2 and 5.3 MJ/brick. On the other end of the scale, older beehive kilns can consume around 21.1 MJ/brick. Process modifications in brick production could yield large savings in energy use and CO_2 emissions. Technical improvements in burners, air blowers, and "slashing" processes (heating the kiln to excessive temperatures to color bricks for cosmetic reasons) could yield substantial reductions in energy consumption (Brick Institute of America, 1994).

20.3.4.3. Glass

In 1991, the United States produced 20.8 Mt of glass, at 7.4 to 8.4 GJ/t. Of this, 2.2 Mt of flat glass, at 7.4 to 8.4 GJ/t, was manufactured for use in the automotive/transportation and construction industries; 2.0 Mt of fiber glass, at 6.3 to 10.6 GJ/t, was produced for building insulation and a variety of building and product materials. The industry uses mostly natural gas as its energy source, along with some electric furnaces (Ross, 1991).

20.3.4.4. Wood

Wood is a far less energy-intensive building material than steel, concrete, brick, or glass; it provides superior insulating properties; and because of its relatively low density, it has lower transportation-energy requirements. Koch (1992) uses the CORRIM Report (NRC, 1976) to estimate the following embedded energy in residential building materials compared to wood:

- Steel structural building studs (9 x wood)
- Synthetic fiber floor covering (4 x wood)
- Concrete floor (21 x wood)
- Aluminum siding (5 x wood)
- Brick veneer (29 x wood).

An update clearly is needed, to take into account efficiency improvements in each industry.

20.3.5. Food Products and Light Manufacturing

The energy contributions to the food and beverage sector are modest in developing countries but are substantial in industrial nations. Pimintel (1973) has estimated that each U.S. food calorie requires approximately 10 technological calories to grow, transport, refrigerate, and prepare it, partly because the average food travels 2,092 km from the field to the consumer. Significant amounts of energy are expended in refrigeration and food processing, and a large amount of energy is embodied in packaging. For example, in 1991, the United States produced 13.5 Mt of container glass at 7.4 to 8.4 GJ/t, for a total of 114 PJ (Ross, 1994).

In light industry, major GHG reductions are likely to come from improved efficiency in space conditioning and lighting and the replacement of motors and belts with more-efficient ones. In the textile industry, the embodied energy of different fibers suggests that cellulosic fibers may have the lowest values, followed by synthetic petrochemical fibers and conventionally grown natural fibers, which rely heavily on fertilizers and industrial-style agriculture.

20.4. Technical Abatement Options

20.4.1. Fuel Substitution

Fuels with low or zero CO_2-generation potential can be substituted for fuels with high CO_2-generation potential to reduce GHG releases. In general, coal and oil are replaced by natural gas, renewables, and nuclear. For the industrial sector, substitution of coal with natural gas is most relevant. A major study at the International Institute for Applied Systems Analysis (IIASA) on historical trends of energy and fossil-fuel carbon emissions shows that most economies have reduced their energy intensity as industrialization has proceeded and that the carbon content of global energy use has been falling monotonically. The carbon intensity of energy consumed currently is about 0.5 t C/kWyr—down substantially from a value of 0.8 t C/kWyr in 1860 (Nakicenovic *et al.*, 1993).

20.4.1.1. Low-Carbon Fuels

The direct use of low-carbon fuels, such as natural gas, rather than coal in industry can substantially lower carbon dioxide levels. However, the lower price of coal and its much greater abundance have made it the fuel of choice in the absence of incentives or regulations to lower GHGs.

20.4.1.2. Electrification

World economies are becoming more electrified. In the United States, for example, electricity increased from 15.9% of purchased energy in 1974 for six major industrial groups (petroleum and coal products, building materials, paper, chemicals, primary metals, and transportation equipment) to 22.5% in 1988 (GCC, 1993). The implications of this shift for GHG emissions are unclear. Proponents of increased electrification point out that this process often leads to efficiency gains that offset additional CO_2 releases. Additional reductions in GHG emissions are likely to be realized when the direct combustion of fossil fuels is replaced by electrical generating capacity from nuclear, hydro, biomass, or renewable sources. Additional gains can arise when low-temperature industrial process or space heat is supplied by heat pumps rather than by the direct combustion of fossil fuels. Although total energy use in the OECD industrial sector has remained essentially constant during the past 20 years, CO_2 from the industrial sector actually declined by 9.6% between 1970 and 1990 (di Primio, 1993).

On the other hand, electric utilities constitute the largest source of CO_2 in many economies. Di Primio (1993) has identified transformation and distribution losses for electric power production as a principal contribution to CO_2 emissions in both industrial and developing countries, and this percentage has increased with time. The percentage of CO_2 arising from power plants was 22.6% for OECD countries in 1970 but had increased to 29.8% in 1990. For the United States, the increase was even greater: from 23.4% in 1970 to 32.7% in 1990. In the late 1980s, 36.4% of CO_2 came from power plants in India, 19.8% in China, and 32.5% in the former Soviet Union.

In short, the effect of increased electrification on industrial CO_2 releases depends on the particular purpose for which electricity is substituted, the carbon intensity of the source of electric power relative to the direct combustion of fossil fuels, and the structure of a given industrial economy.

20.4.1.3. Biomass

The use of plant material as fuel and feedstock in place of fossil fuels can have a significant effect on the reduction of net CO_2 emissions. Although cellulose releases approximately the same amount of carbon as coal per unit of energy produced, this release of CO_2 is largely offset by the absorption of CO_2 from the atmosphere as biofuel is regrown. Immense potential exists for energy recovery from organic municipal and industrial wastewaters through efficient biomethanation processes (Khanna *et al*., 1988). Alcohol biomass fuels have played a major role in Brazil (Goldemberg *et al*., 1993), and plantations could provide significant biofuels in many countries (Hall *et al*., 1994). A full discussion of liquid fuels and biofuel plantations is included in Chapter 19.

Ironically, although biofuels constitute a major energy source in many developing countries, it is the United States that is the leader in generating electricity from biomass. According to the Electric Power Research Institute (Turnbull, 1993), biomass electric power generation increased from 200 MW in 1979 to 6,000 MW in 1992, plus 1,800 MW of municipal-solid-waste-to-energy facilities. All of the existing generation facilities use conventional steam technology, often at lower temperatures and lower efficiencies than fossil-fuel facilities. Much of this power production from biomass is associated with industries like wood, paper, and food processing that use their own waste. The growth of biomass-fueled facilities in the United States has not been matched in other industrialized countries. This is primarily because of the presence of a regulatory regime in the United States that encourages industrial power production.

Several examples of biomass electric-generating facilities also exist in developing countries. Bagasse is sometimes burned in India, Mexico, and Brazil at sugar refineries for heat and some electricity. A 5-kW diesel generator, modified to burn biomass produced from cow dung and agricultural wastes, produces electricity in Pura, India (Rajabapaiah *et al*., 1993). The potential for greatly improving the efficiency of biomass power systems lies in the introduction of highly efficient gas turbines coupled to biomass gasifiers, according to Williams and Larson (1993). Their analysis suggests that the 80 cane-growing countries of the developing world have sufficient bagasse and other sugar-cane residues to support such facilities.

20.4.1.4. Renewable Energy Resources

In sunny regions, including many tropical countries, solar drying opportunities exist for grains, specialty fruits and vegetables, sugar cane, and lumber. Solar drying also can be applied to biofuels, whose moisture reduces their effective energy content. For example, approximately half the weight of bagasse from sugar cane is water; when moist, it releases only 9,042 kJ/kg, but when dry, it releases 19,424 kJ/kg (comparable to lignite) (Brown, 1987). In addition, by removing the weight of incorporated water, solar drying can reduce the energy requirements to transport biofuels, lumber, grain, and other products. Existing solar water-heating technology is well-matched to the process-heat levels required by such industries as food processing and textiles and for the curing of plastics, resins, and adhesives.

Few examples can be found of on-site use of solar or wind energy for industrial processes. These intermittent resources would need to be supplemented by grid or conventionally self-generated electricity, used in accord with the availability of wind or solar power, or disengaged from the demand for power through storage devices (Moomaw, 1991). This suggests that electroplating and other electrolytic chemical manufacturing (e.g., the production of chlorine and sodium hydroxide) might also be suitable for self-generated solar or wind energy. Another possible use of wind or solar energy in manufacturing would be for pumping industrial water that could be stored for use on demand (Lonrigg, 1984).

20.4.1.5. Hydrogen

Although hydrogen releases no CO_2 when burned or reacted chemically, it is mostly derived from CH_4, which produces CO and CO_2. Several alternatives are possible for producing hydrogen without carbon emissions. It is estimated that it would cost between \$9 and \$19/GJ to produce hydrogen by off-peak hydroelectric-based electrolysis costing between 1 and 4¢/kWh. Biomass gasification could lower the cost to between \$5.9 and \$8.5 per GJ (Ogden and Nitsch, 1993). Were the cost to drop sufficiently, considerable reductions in GHGs would occur in the primary-metals industry because of the use of hydrogen to reduce oxide ores.

It has been suggested that photovoltaics are ideally suited as low-voltage DC sources of electricity for the electrolysis of water to produce merchant hydrogen where it is needed (Ogden and Williams, 1989; Ogden and Nitsch, 1993). The auto manufacturer BMW has built a 600-kW photovoltaic test facility with Siemens and the Bavarian government to produce hydrogen automotive fuel.

20.4.2. Energy Efficiency

Energy efficiency in industrial plants can be improved through opportunities on the end-use side (such as variable-speed electrical drives and insulation) and opportunities on the conversion side (such as cogeneration applications and advanced boilers).

20.4.2.1. Efficient Electrical End-Use Devices

Electrical motors are major consumers of industrial electricity. Several studies in the United States conclude that approximately two-thirds of electricity is consumed by electrical motors, with the industrial sector accounting for between 26 and 30% of the total. These motors are used primarily to drive pumps, compressors, and fans. Major opportunities exist to improve the efficiency of the motors themselves and the systems, connecting shafts, and belts they drive (U.S. DOE, 1980; Baldwin, 1989).

Standard motors operate with an efficiency of 70% for small devices of a few kilowatts, to 92% for large motors of 100 or more kw. High-efficiency motors operate in the range of 83 to more than 95% (Baldwin, 1989). One analysis of an industrial pumping system showed that only 49% of the energy output of the electric motor actually was converted into work to move the liquid (Baldwin, 1989; U.S. DOE, 1980). Optimizing system design rather than simply choosing components can lead to improvements of 60% using existing technology (Baldwin, 1989). A study of Indian industrial efficiency found that replacing traditional power-transmission V belts with modern flat belts could improve efficiency from 85 to 98% (NEERI, 1993). This study, along with Baldwin's, also demonstrates the potential for adjustable-speed electronic drives to better match mechanical load, substantially reducing electricity use.

The U.S. Environmental Protection Agency (EPA) has estimated that 12% of U.S. utility CO_2 emissions—55 Mt C—could be eliminated by replacing existing lighting systems with cost-effective lighting technology (U.S. EPA, 1993). Industry represents one of the largest users of lighting. The voluntary Green Lights program had enrolled more than 1,255 corporations, institutions, and state and local governments by early 1994, all of whom are committed to replacing 90% of their lighting with cost-effective, efficient substitutes within 5 years (U.S. EPA, 1994). Computers are estimated to consume approximately 5% of U.S. electricity; EPA has developed the Energy Star program, which has produced significant declines in the electricity use of new computers and other office equipment now entering the market. The average power demand of different types of computer printers was found to range from as little as 3 to as much as 129 W in one study (Norford *et al*., 1989). Although these ancillary devices represent a small fraction of total industrial energy use, there is substantial room for significant savings. The surprising success of voluntary programs in the United States suggests that this approach should be more widely utilized in other countries.

20.4.2.2. Cogeneration and Steam Recovery

In cogeneration facilities, fuels are burned and the heat produced is used both for generating electricity and for process heat. Cogeneration schemes are of two kinds: topping-cycle and bottoming-cycle. In topping-cycle cogeneration, primary energy (the high-temperature energy, generally about 1,500°C) is used to produce electricity, and the low-temperature heat that emerges from the generator is used for process or space heating (e.g., to dry pulp in a paper mill). In bottoming-cycle cogeneration, primary energy is used to produce heat (e.g., to anneal steel), and the leftover heat is used to generate electricity.

Cogeneration facilities generally use as much as 80% of the heat content of fuels, significantly reducing the amount of CO_2 produced compared to facilities where electricity and heat are produced separately. A variety of technologies now are employed that continue to improve the overall efficiency of cogeneration. Conventional steam turbines that recover a portion of waste heat are being displaced by higher-efficiency and less-costly gas-turbine cogeneration systems and combined-cycle systems that use some of the heat from the gas turbine to run a lower-temperature steam turbine as well as to provide process steam (Williams and Larson, 1989). In the United

States and many European countries, many small-scale cogeneration facilities have been developed in the industrial sector as the result of new technological developments and changes in the laws governing electrical utilities. Industries are now permitted to sell surplus electricity to the utility grid, and utilities are required to purchase it at favorable prices. Since the change in legislation, a majority of the new electric-generating capacity constructed in the United States has been from manufacturing, pulp and paper, and other industrial or independent cogenerators rather than large utilities. The U.S. Office of Technology Assessment has estimated that industrial cogeneration could reduce industrial energy demand by 140 TW/yr in the United States by 2015 (OTA, 1991).

Substantial cogeneration is carried out in Western Europe, especially in Finland, Denmark, the Netherlands, Sweden, and Germany. Because of regulatory constraints and climatic conditions (large air-conditioning demand), Japan was slow to adopt cogeneration relative to other industrial nations. The Japanese electric utility industry law was revised in 1995 and may now facilitate the spread of cogeneration in that country. Because of the large amount of heavy industry and extensive district-heating systems already installed in the former Soviet Union, an enormous potential for major reductions in CO_2 also exists there through the adoption of industrial cogeneration.

20.4.2.3. Waste-Heat Utilization

Even in countries where high levels of industrial energy conservation have already been achieved, a large potential still exists for further industrial heat recovery. Data from a survey conducted in 556 representative factories in Japan indicate that almost half of the surplus heat that currently is discarded has potential for use. From a total of 1.8 EJ surplus energy generated by these factories, about 0.5 EJ already has been used effectively as steam, process gases, or electricity—a 2.7% decrease in primary energy consumption. Unexploited-energy figures for the four main energy-consuming industries in Japan are shown in Table 20-5. The unexploited surplus energy from these industries amounts to almost 1 EJ, of which about 48% has a potential for economic use (Kashiwagi, 1991).

The first step in planning energy utilization is to carefully map the flow of energy in each industry, from primary energy or electricity input to the lowest-temperature waste-heat output. Once these flows are known—including the quantity (e.g., kilowatts) and quality (e.g., temperature levels, voltage, and frequency)—industrial processes can be integrated, initially within each industry, to minimize the input of primary energy and/or electricity.

Cascaded energy use involves fully harnessing the heat produced by fossil-fuel combustion, from its initial 1,800°C down to near-ambient temperatures, with a thermal "down flow" of heat analogous to the downward flow of water in a cascade. If a water flow were to be used to generate electricity, for example, a dam would first be built on a mountain; then a succession of power-generation plants would be set at strategic points down the river to use up heads of water. Once the river water had flowed to sea level, it would have become useless for electricity generation. The heads of water at each generation plant are analogous to temperature gradients in thermal energy; sea level corresponds to ambient temperature. As in the case of river water reaching sea level, heat that has cooled to ambient temperature no longer is usable. Currently, even in the industrial sector, there are extremely few cases of heat being used in multiple stages (cascaded) akin to hydroelectric power generation.

Based on the ideal energy flow among industrial processes classified by their temperature levels, Kashiwagi (1992) suggests a representative example of ideal exergetic utilization of fossil fuel resources in a temperature cascade that utilizes combined heat and power and renewable energy, as shown in Figure 20-2.

In an effort to construct district-heating systems using unexploited energy sources, several countries have been promoting

Table 20-5: *Unexploited energy of the largest energy-consuming industries in Japan (joules).*

			Paper Pulp[2]	Chemical Industry[3]	Cement	Iron and Steel[4]	Total
Energy Flow	Energy Input		4.2 x 10^{17}	1.5 x 10^{18}	2.6 x 10^{17}	1.8 x 10^{18}	4.0 x 10^{18}
	Unexploited Energy[1]	Usable	1.1 x 10^{16}	–	2.6 x 10^{15}	4.9 x 10^{17}	0.5 x 10^{18}
		Unusable	1.2 x 10^{17}	1.9 x 10^{16}	5.1x 10^{16}	3.3 x 10^{17}	0.5 x 10^{18}
		Total	1.4 x 10^{17}	1.9 x 10^{16}	5.4 x 10^{16}	8.2 x 10^{17}	1.0 x 10^{18}

1 Amounts of unexploited energy are estimates based on models for the four industrial sectors, thus may differ in precision depending on the model adopted.
2 Estimates for the paper and pulp industries presuppose increases in effective use of black liquor.
3 For the chemical industry, even if supply and economic conditions are fulfilled, there are almost no prospects; unexploited energy for the chemical industry refers to the ethylene sector only.
4 Values of energy input and unexploited energy for iron and steel industries based on examples of combined steel and iron manufacturing.

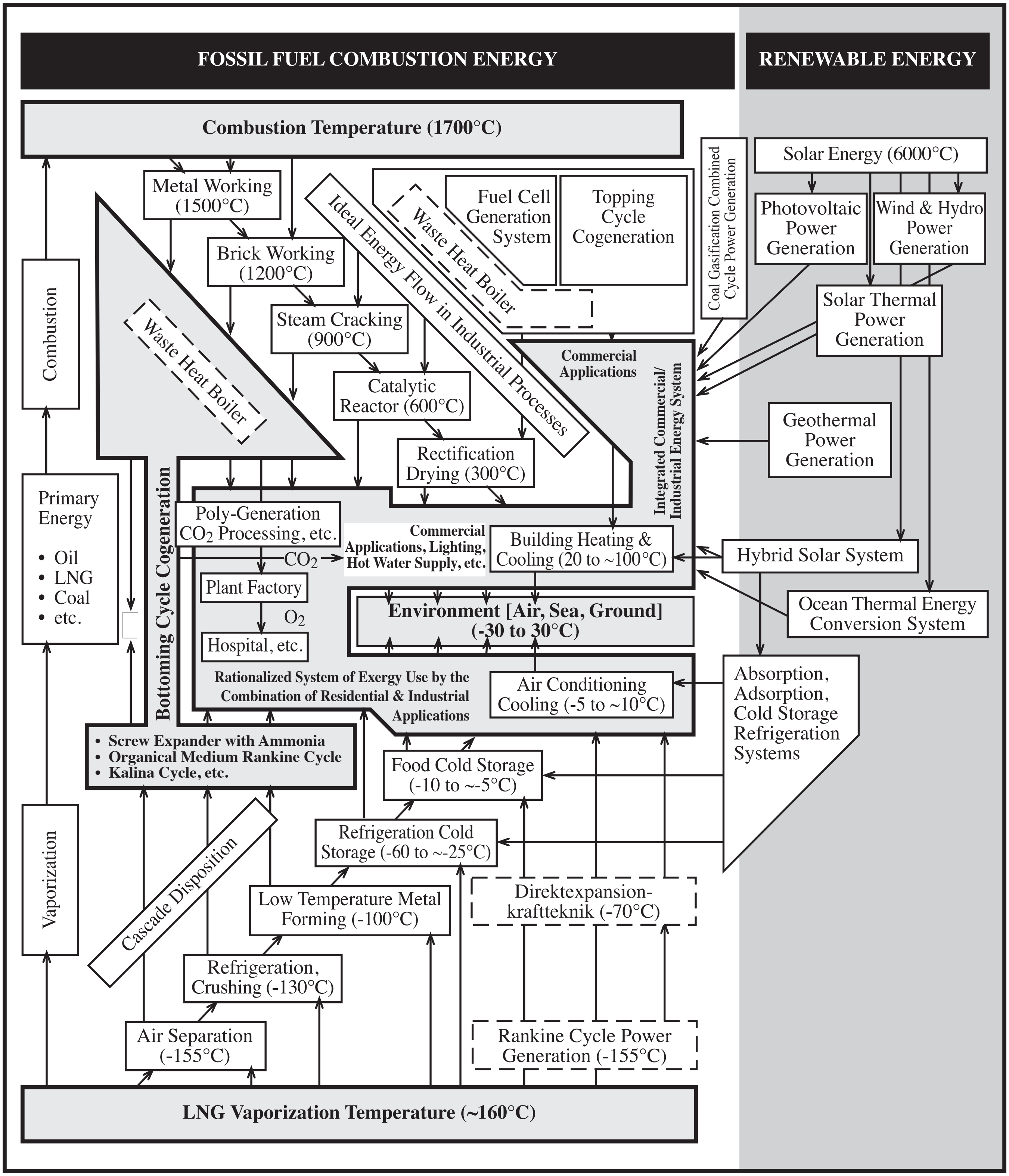
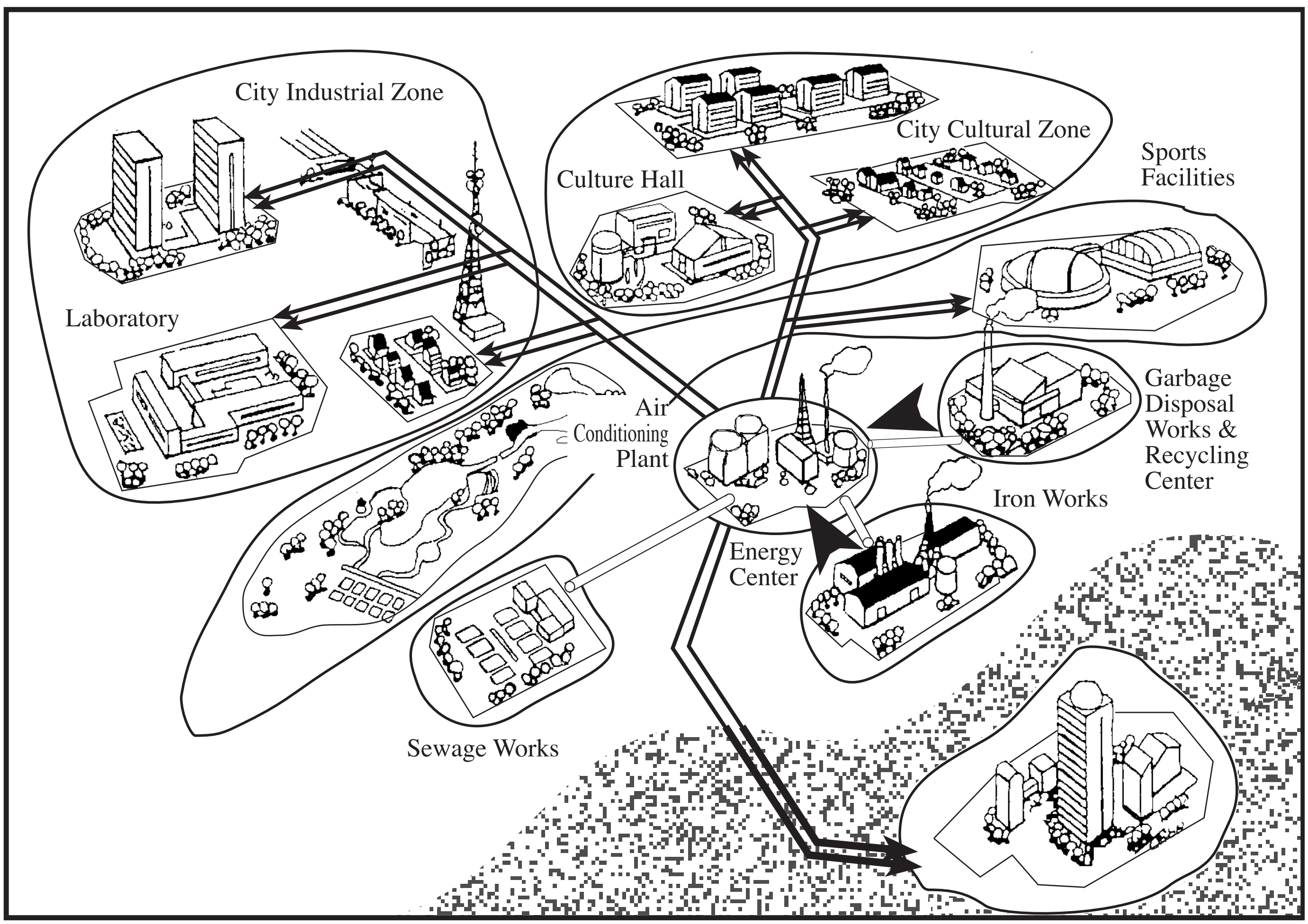


Figure 20-2: Cascaded energy utilization concept in an integrated industrial/urban system.

research and development (R&D) on large-scale, high-efficiency machines; heat-transport technologies; large-scale heat storage; and optimized systems combining these technologies. Expansion of district-heating systems brought on by dramatic increases in the efficiency of unexploited-energy utilization systems is expected to reduce and optimize energy consumption—and, hence, to help shave off the peak of electric power demand.

Thyssen Stahl AG produces 10 Mt of steel each year in Duisburg, Germany, where demand for space heating is high and district-heating systems are well developed. Heat is recovered from its high-temperature furnaces as steam at 480°C and 1.4 MPa for driving electric-power-generating turbines and also as hot water (150°C) for supply to 15,000 of 45,000 nearby households served by the local district-heating system. Because the point-of-use temperature of the hot water must be kept between 90 and 95°C, the operating company of the district-heating system has installed natural-gas boilers to make up for fluctuations in heat demand and/or temporary stoppage of the high-temperature furnaces.

The conception of the Onahama hot-water supply system in Japan dates to the 1960s. A coke factory owned by the Nihon Kasei conglomerate in Onahama, Fukushima Prefecture, had been using seawater to cool high-temperature process gases in its facilities. A feasibility study conducted by Nihon Kasei in 1965 showed that this industrial surplus heat could potentially be used in the nearby Onahama area. Encouraged by these results, the city mayor formed a preparatory committee for the establishment of a hot-water supply company in Onahama, which was run by local associations of commerce, tourism, fishing, and inns. The heat-supply system included a pipeline of more than 10 km, pumps, heat-storage tanks, high-speed filters, and chlorination facilities. Freshwater now is supplied to the factory as a process-gas coolant, with a hot-water output of 10^5 m^3/h at 63°C. After filtering and chlorination, the hot water is pressurized by pumping so that the return pressure always exceeds 10^6 kg/m^2. The point-of-use temperature of this hot water always is maintained at or above 50°C. Monthly water-quality tests carried out by Fukushima Prefecture sanitary



	Half-Million People City	Four-Million Ton Scale Iron Works
Power Consumption	2.0 x 10^8 W	2.5 x 10^8 W
Drainage	1.5 x 10^5 t/day	1.5 x 10^5 t/day
Gas Use (at 41.9 MJ/N m^3)	2.4 x 10^5 Nm^3/day	2.7 x 10^6 N m^3/day
Heat and Hot Water Supply	7.95 x 10^{12} J/day	32.2 x 10^{12} J/day

Figure 20-3: Urban-level energy system with industrial waste-heat utilization.

authorities have consistently shown this hot water to be on par with potable water, which makes it suitable not only for bathing and washing clothes but also for dishwashing.

Large-scale energy conservation will require the establishment of urban-level energy systems supported by industries. Figure 20-3 provides a schematic of this concept, in which a city of 500,000 people would use waste heat from a 4 Mt/yr iron works. An air-conditioning plant and energy center would provide heating and cooling to the city using heat received from the iron works and from a garbage-incineration plant. The figure indicates that the urban demand for energy could be met by using waste heat from the factory. Factories with high energy consumption can use that energy more effectively by conserving energy and using waste heat.

The future technology of broad-area energy utilization systems would involve an advanced cascaded and combined thermal energy-recirculation system based on innovative technology that recovers waste heat from facilities and transports the recovered energy efficiently to remote urban areas. This concept is illustrated in Figure 20-4.

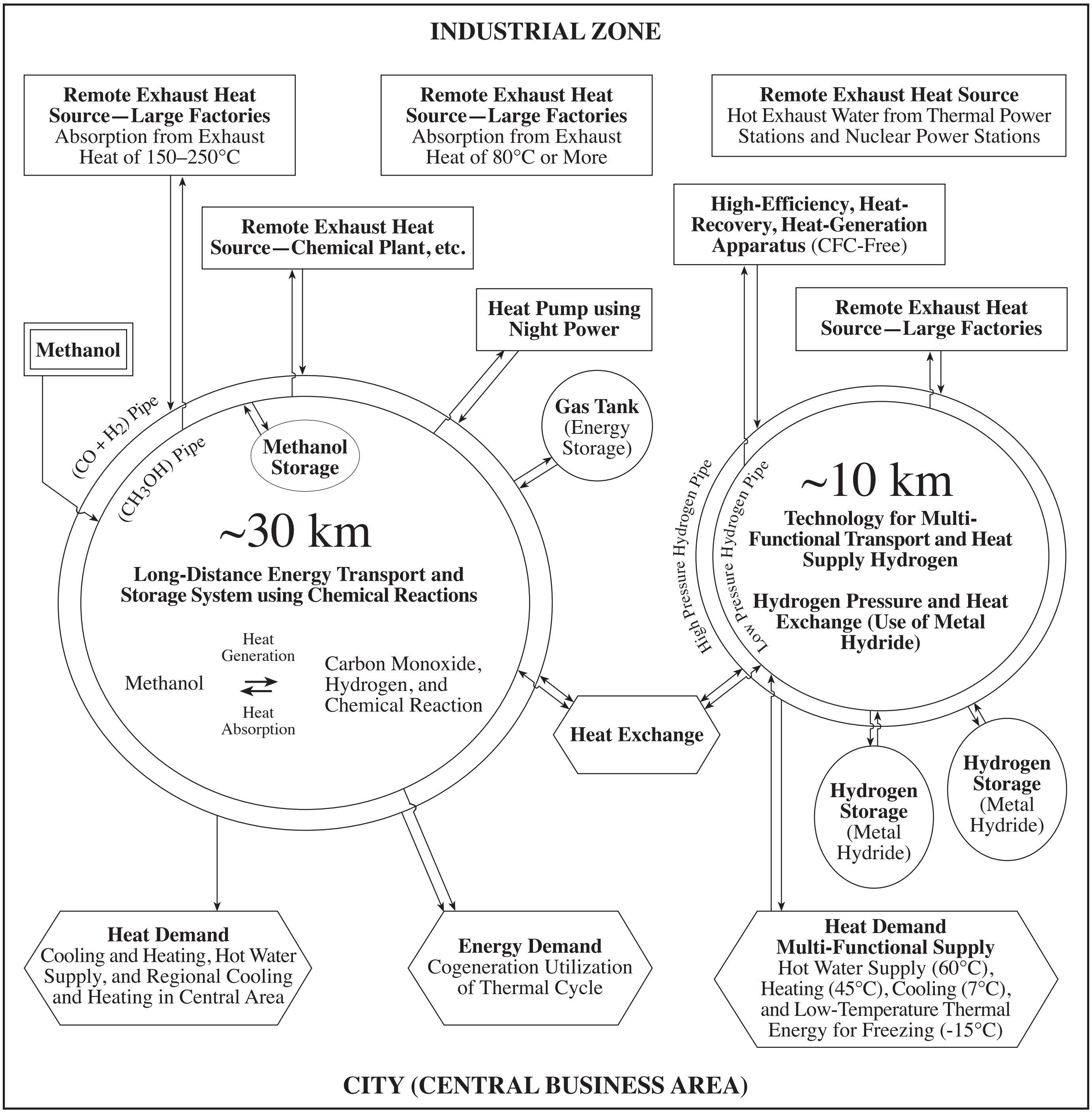


Figure 20-4: Schematic of the area-wide energy utilization network.

To implement this concept, major breakthroughs would be required in two main areas. First, key technologies would have to be developed: heat recovery with a maximum utilization of sensible heat and with a temperature-lifting capability; heat transport and storage technology that employed chemical reactions; and multifunctional heat supply technology. Second, the total system would have to be structured and optimized by matching multiple and wide-area heat sources to the energy demand, which would be supported by industrial energy centers as seen in Figure 20-5.

One estimate for Japan indicates that if unexploited energy in coastal industrial regions near major urban areas were used to the maximum extent, national energy consumption would be reduced by 6% and CO_2 emissions would be reduced by 9% (Kashiwagi, 1992). A system that utilizes high-temperature heat from electric power-producing gas turbines to boost the lower-temperature heat from municipal waste incineration to run steam turbines and provide district heat has been described (Lindemann, 1992; NEDO, 1993). Industrial centers based on sound land-use planning and industrial ecology principles—where waste materials and heat from one production process are utilized by nearby industries—have been attempted only in a few places, such as Kalundborg, Denmark (Frosch, 1995).

20.4.2.4. Materials Recycling and Reuse

When goods are made of materials whose manufacture consumes considerable amounts of energy, the recycling and reuse of those goods can save not only energy but GHGs released to the atmosphere. However, recycling usually involves complex tradeoffs. For example, a car with an aluminum frame is lighter than a car with a steel frame—and thus consumes less energy for the same transportation service—but its own energy content is higher because the energy content of aluminum is higher than that of steel. Using returnable glass bottles instead of plastic bottles for mineral water (i.e., artifacts with a much longer lifetime—the average returnable glass bottle being used 18 times, for example, in Europe) reduces the amount of energy embodied in the materials needed for the same service but increases the energy embodied in collecting, transporting, and washing the bottles. Moreover, lengthening the lifetimes of durable goods may hinder the diffusion of new generations of goods or techniques that emit less CO_2. Assessing the emissions benefits of such actions, therefore, requires careful life-cycle analysis.

Recycling of energy-intensive materials undoubtedly has increased during the past 10 years, mostly in industrialized

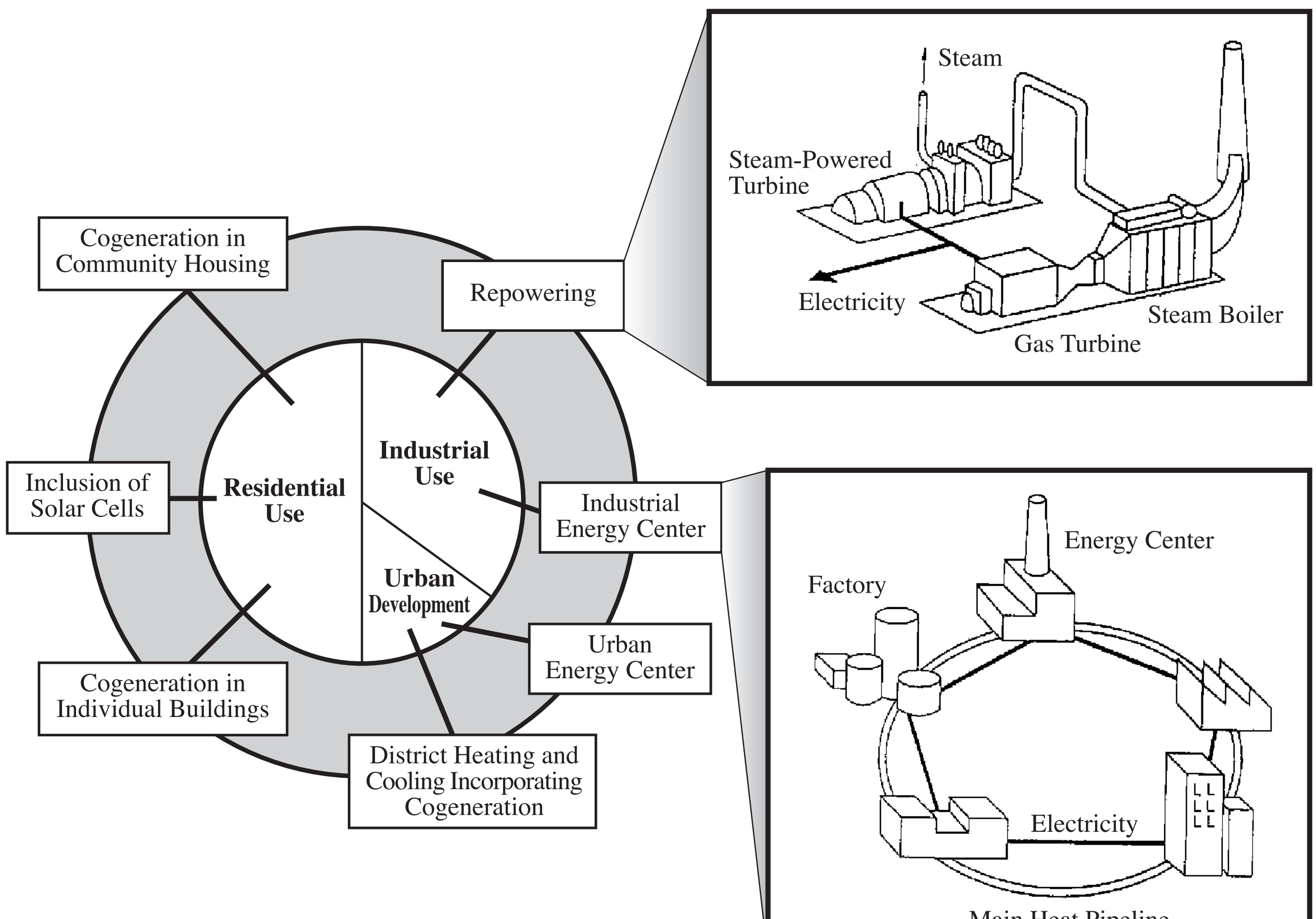


Figure 20-5: The structure of industrial energy centers.

countries. Data on present recycling rates, however, are diverse. The rate of rough steel produced from scrap is about 43% worldwide (IISI, 1993). In OECD countries, the recycling rates of nonferrous metals are 30% for aluminum, 35% for copper, 48% for lead, 25% for zinc, and 20% for tin (Metalgesellshaft, 1988). The recycling rate for paper is estimated to be 30% at the world level, which also is the rate estimated for the present recycling of glass bottles in OECD countries (IIASA, 1993). Reliable rates for plastics are difficult to arrive at, though they seem to be increasing. Recycling data for developing countries are scarce. In some developing countries, such as India, recycling is significant—a great proportion being carried out by the "informal sector" (Konishi, 1995).

Differences in recycling rates among countries yield a first approach to the existing potential. In Japan, for example, rates for paper and glass bottles were expected to reach 55% by 1994 and rates for steel and aluminum cans to reach 60% in 1995. In Europe, voluntary agreements between administrations and business organizations have been signed to reach recycle rates of 60 to 70% for packaging materials and about 75% of the material content of automobiles before the end of the century. All of these figures are well above world averages. Public measures to improve recycling of materials also must strike the right balance among collection, sorting, and reusing activities. This balance is rather unstable at present and has led in extreme cases to a collapse of secondary-materials markets, thus frustrating further developments.

One must recognize that returning the secondary resource into virgin-grade material is not always necessary or desirable. By analogy to heat recovery of lower-temperature heat through cascading processes, materials recovery can be envisioned as a materials-cascading process in which secondary materials may be used most efficiently for different purposes than are virgin materials. To optimize recycling and reuse potential, materials and products must be designed for recovery as well as for their initial intended purpose.

A summary of carbon emissions from primary and secondary materials production for OECD countries is presented in Table 20-6. Primary materials release about four times the CO_2 of secondary materials for all substances except aluminum (where the figures are substantially higher). Carbon savings of 29 Mt for a 10% increase in OECD recycling of each of the materials also is listed.

20.4.4.5. Dematerialization and Materials Substitution

A number of possibilities for reducing industrial greenhouse gases arise from the management of materials rather than of energy. Dematerialization (decreasing the amount of a material or substituting lighter-weight material for it) can play a major role in lowering GHG emissions (Grubler *et al*., 1993; Herman *et al*., 1989). Energy-related CO_2 also can be reduced in manufacturing by substituting less energy-intensive materials for more energy-intensive materials. Materials that release significant quantities of process GHGs during production can be replaced with materials that release fewer process GHGs (e.g., replacing aluminum with plastic lowers carbon and fluorocarbon emissions). Developing fundamentally new processes that use intrinsically less energy or are dependent on completely different feedstocks such as dry process for paper making, also can lower CO_2 releases.

The use of plants as a source of chemical feedstock also can reduce CO_2 emissions. Many large wood-products companies already produce chemicals in association with their primary timber or paper production. In India, a major effort to develop a "phytochemical" feedstock base has been underway at the National Environmental Engineering Research Institute. The production of chemicals such as acetone, butandiol, butanol, and isopropanol utilizing water hyacinth, grass, and industrial waste as feedstocks has been demonstrated to be technically feasible. The same institution also has been working to develop processes to improve the production of CH_4, as well as microbial conversion of CH_4 to methanol (Motwani *et al*., 1993; Juwarkar *et al*., 1994; Sharma *et al*., 1994).

20.5. Policy Options

Industrial GHG reductions can be achieved by good housekeeping (operational performance), additional investments in energy-efficient technologies (both conversion and end-use equipment), or redesigning the manufacturing process itself (process innovation and integration). Clearly, the technical and

Table 20-6: *Tons of carbon saved and released in primary and secondary materials production.*

	OECD C Reduction for 10% Increase in Recycling (Mt C/yr)	Primary	Secondary	Primary/ Secondary
Steel	18.9	0.65	0.15	4.33
Aluminum	5.0	3.52	0.09	40.04
Copper	0.44	1.08	0.22	4.96
Glass	0.68	0.20	0.04	4.92
Paper	3.74	0.29	0.07	4.00

Source: IIASA, 1993.

***Table 20-7:** Overview of implementation measures and level of impact.*

	Type of Barrier Information and Training	Financial and Economic	Institutional and Legal
Operational Performance	Plant audits Energy management courses	Consultancy grants or subsidies	Energy management centers Engineering consultancy network
Investment in Energy Conversion End-Use Equipment	Product information Specialized courses	Investment subsidies Trade tariff exemptions Market pricing of energy	Performance standards DSM-oriented utilities Demonstration projects
Process Innovation and Integration	Pinch technology Exergy analysis Life-cycle analysis	Internalization of environmental costs	Voluntary agreements R&D programming Land-use planning

financial consequences of these approaches become increasingly important and the role of management becomes correspondingly pervasive. Most industrial facilities and processes have a relatively short lifetime—on the order of a decade or, at the most, 20 years. Hence, there is plenty of opportunity to introduce low-GHG-emitting technology into the manufacturing process as part of normal capital-stock turnover. Unfortunately, under present circumstances, there are no compelling incentives for companies to choose a lower-GHG-emission strategy over a higher one when they are planning new processes or products. Hence, there is a need for additional policy instruments and incentives, some of which are described in this section.

Even when efficiency improvements and greenhouse gas reductions are feasible from a technical perspective, there remain a number of barriers that still may prevent the realization of such improvements. First, a company must be aware of the opportunities that are available. Second, there may be capital constraints such as unfavorable pricing of energy or recycled materials. Third, institutional and legal measures may be necessary where financial and economic incentives remain weak and markets for efficient equipment are just emerging. In some cases, additional research may be needed to develop appropriate energy-efficient technologies, material-efficient applications, or nonpolluting manufacturing processes. Table 20-7 provides a survey of implementation measures according to the type of barrier encountered.

20.5.1. Providing Information and Training

Reduction of greenhouse gases from industrial sources can be promoted by a variety of information-related policy steps on the part of individual firms, industry groups, or governments. Technical guidance can be provided to industrial managers to help identify opportunities to alter techniques of managing energy and materials in the manufacturing process, toward the goal of reducing energy use and GHG emissions.

Consumers often lack information about the environmental consequences of their purchases and seldom consider energy and other life-cycle costs in their purchasing decisions. Energy-efficient appliances, for example, may have higher purchase prices but during their lifetimes cost less for the consumer to operate. The economic disincentive of higher purchase prices might be overcome by better information and labeling about the life-cycle costs and environmental impact of manufactured goods.

20.5.2. Fostering Technology Transfer

Because future global industrial growth will take place largely in the developing and transitional economies, the early transfer of advanced energy-conservation technology may be crucial to curb worldwide GHG emissions. Developing countries might even jump from an early stage of industrial development to an advanced stage in one step. Such leapfrogging makes sense only if the new technology is economically superior to the old technology over its life cycle and if capital is available to purchase it. This may be the case only for isolated, large-scale, turn-key projects that usually are associated with multinational corporations or multinational lending agencies. The applicability of the concept across the spectrum of efficiency options needs careful scrutiny. In many cases, judicious adaptations may be called for, particularly to enable the manufacturing of major components by local industries.

In regard to technology transfer, two issues are still unclear. One is trade barriers in the form of import tariffs and legal barriers for the protection of intellectual-property rights. Such barriers affect the adoption of high-tech components of energy-efficient equipment. A balance must be struck between the interests of developing nations and the interests of industrial firms elsewhere. Ongoing economic globalization and the increasing involvement of foreign investors in many developing countries—including, in the recent past, both China and India—may be symptomatic of changing attitudes on both sides. This development follows in the wake of economic liberalization and shows the importance of institutional aspects for effective technology transfer.

The other issue is the establishment of mechanisms for financial transfers, in particular within the framework of the Global Environmental Facility and Joint Implementation. Energy efficiency is high on the list of priorities in this respect. At present, the future of political modalities for technology transfer still is not clear. Political controversies surrounding joint implementation involve complicated issues regarding responsibilities and credits and are far from resolved.

Nevertheless, joint implementation could potentially be viewed as a mechanism to make private capital available for the transfer of energy-efficient technology. This possibility is particularly true for the industrial sector, where multinational firms are keen to avoid the increasingly steep costs of GHG emissions in some countries if attractive alternatives are available elsewhere. In some cases, utilities from industrial nations are already actively exploring potential opportunities.

There also needs to be a better mechanism for making available new industrial ecology management systems, like that used in Sweden (Graedel *et al*., 1994), that encourage lower GHG emissions.

20.5.3. Financial and Economic Policies

Conservation opportunities may not be profitable from the perspective of the private investor due to unfavorable pricing of energy or lack of capital. Financial and economic measures are then required.

20.5.3.1. Subsidizing Energy Audits

The first step toward energy improvement requires managerial awareness of the potential benefits of saving energy and an accurate overview of how and where energy is used in the factory and at what costs. Tax credits for plant audits and consulting may help to initiate energy-saving programs by identifying opportunities for good housekeeping and by indicating where energy-saving investments would be technically possible and financially profitable.

20.5.3.2. Providing Fiscal Incentives for the Purchase of Energy-Efficient Equipment

The next step requires a proper market for energy-efficient equipment (cogeneration systems, efficient boilers and furnaces, heat exchangers, electric drives and pumps, insulation materials, and advanced control systems). Fiscal incentives in the form of tax credits may help an emerging market for such equipment to mature. Adequate performance standards and active involvement from utilities will create legal and institutional support at this stage. Finally, in order for decisions about new processes and factories to be guided by energy-cost considerations, attention to plant energy costs will be stimulated by a firm government commitment to long-term energy-demand policies, correcting market distortions from environmental externalities, researching demand-side priorities, and land-use planning (where system-integration aspects are crucial).

Implementation problems for energy-efficiency improvements in developing and transitional economies are more severe than those in industrial countries. In addition to problem areas already indicated, key problems in both developing and transitional economies concern the economy-wide lack of capital, foreign exchange, and industrial energy prices and tariffs that often are below those of the world market. Because energy-saving investments often are characterized by capital and foreign-exchange intensity rather than by labor and resource intensity, their cost-effectiveness tends to be less in those countries than in the industrialized countries. Moreover, developing and transitional economies, in general, are characterized by lower overall productivity, including energy productivity. One should not attempt to solve energy-efficiency problems in isolation from other efficiency problems. Problems related to vintage equipment, scarcity of management skills, small-scale production, or poor technological infrastructure will not be solved by addressing climate-change or energy goals alone.

Market-oriented energy pricing is the first step in raising energy-efficiency priorities in all economies, regardless of their state of development, and already is receiving attention in most developing and transitional economies. The problem of capital and foreign-exchange scarcity has a more permanent and pervasive character. Although taxing environmental externalities is desirable, many industries operate on an international level, so the introduction of such taxes requires international action. Unilateral correction of national market prices can lead to a loss of international competitiveness.

20.5.3.3. Examining Taxation as a Tool

The "material content" of economic growth and its resulting greenhouse effect results from a huge number of interrelated decisions made by economic actors (e.g., business firms and households). Therefore, economic instruments—such as taxes that internalize externalities—seem to be most appropriate policy tools. However, although some assessments have been carried out on the effect of a carbon tax on energy efficiency in different sectors, little work has been done on the effect of such a tax on recycling or material substitutions. We must therefore admit that we do not know the efficiency of economic instruments in this field.

Preliminary results (ADEME, 1993; Gielen, 1993) tend to demonstrate that a carbon tax would mainly influence waste management (increased recycling and/or incineration) and would promote little in the way of material substitutions within products—unless it reaches very high levels and except for products whose material composition has a significant impact on energy consumption in the end-use phase.

Carbon taxes on fuels have been proposed as one way to lower CO_2 emissions from fossil-fuel burning. Interestingly, although the use of carbon taxes on fuels to internalize climate-change costs from that source have been the topic of major discussions, little attention has been given to applying a "greenhouse tax" to process-related releases. In some countries, such as the United States, an "ozone depletion tax" has been applied to CFCs and halons to improve the price competitiveness of substitutes. Such a strategy might be considered for goods whose manufacture produces GHGs.

Internalizing environmental costs in energy prices and tariffs through ecotaxes is particularly problematic for the industrial sector because of the consequences for national competitiveness on international markets. Taxes that are not levied on a global scale may provoke industry relocation, which may adversely affect emissions efficiency as well as international competitiveness. Most countries are hesitant to embark on policy ventures that might endanger their international market position and their attractiveness as industrial locations. Although tax exemptions for specific industries are possible, policymakers are wary about the administrative feasibility and costs of such exemptions. On the other hand, little empirical evidence points to any actual dangers of industrial relocation resulting from ecotax burdens. Because only new investment is affected, the impact of taxation may not be immediately apparent, although the impact may be more pronounced in the future because industries are becoming more international.

Systems of internationally traded emissions permits, carbon taxes, and opportunities for joint implementation are options that require international cooperation. It is difficult for a single nation to impose full environmental cost accounting and remain competitive unless other nations do the same.

20.5.4. Supporting Technical Innovations through Research and Development

During the past two decades, many energy-saving technologies—such as compact fluorescent light bulbs—have been developed with government research support and have successfully penetrated the market. To reach further reductions in energy intensity, more-expensive and less-proven technologies must make a contribution. Energy-conservation programs, therefore, need to devote more attention to research, development, and demonstration than in the past. An appropriate balance between energy-supply R&D budgets and energy-conservation R&D budgets has not yet been achieved. Additional R&D needs to be encouraged in the private sector through appropriate tax incentives.

In several cases, secondary materials similar in quality to primary materials will be available during the coming 10 to 20 years. In these cases, the steady-state rate of recycling will depend mostly on the cost of collecting and sorting. Hence, regulations and policies favoring economic efficiency at the collecting and sorting stage are crucially important. However, for some materials, like plastics, the situation is more problematic. With these materials, obtaining high-quality recycled products or finding uses for recycled low-grade materials seems to remain rather difficult. Hence, public intervention can be essential to promote R&D activities in this field and expand the market for recycled products.

20.5.5. Organizing and Supporting Recycling

Increasing recycling rates is linked to the following measures: limitation of dissipative uses; product design allowing easy-to-treat structures and easy disassembly; standardization of materials to produce more homogeneous scrap; more cost-efficient collecting and sorting; and technical innovation to increase the quality of secondary materials and/or lower their quality requirements in volume markets.

Regulations banning dangerous dissipative uses have been implemented in many OECD countries, particularly for heavy metals. The primary goal obviously was not to limit the greenhouse effect, but the impact on recycling rates was additive. Industrialized countries are putting increasing regulatory pressure on recyclability, mostly driven by solid-waste concerns. This trend is illustrated by recent French and German initiatives concerning packaging wastes. The producers of packaging materials have been made responsible, through voluntary agreements, for setting up organizations (DSD in Germany and Ecoemballage SA in France) to collect, sort, and recycle their materials.

As another example, an ongoing regulatory process within the European Community is aimed at drastically reducing the volumes of industrial and domestic wastes dumped in landfills. The general purpose is to ban the dumping of any type of "unprocessed" waste, thereby limiting landfilling to "ultimate" wastes. Waste "processing" may be recycling and/or incineration with heat recovery and/or power generation—the former being preferred, although it is not clear that clean incineration is always worse for the environment than recycling. For industry, the cost of producing wastes will therefore rise, leading to "material-efficiency" improvements (including internal recycling) within industrial plants.

In many locations, policies dictate that households use different types of receptacles to separate papers, glass, plastics, and organic matter. Such behavior significantly lowers the cost of sorting, improves the homogeneity of scrap, raises the quality of secondary materials and lowers their treatment costs, and ultimately increases the potential rate of recycling. Successes have been reached by several pilot experiences.

Manufacturing materials from scrap tends to be less expensive than from primary raw materials, but secondary materials often cannot be used in all of the applications that primary materials can. Therefore, the maximum rates of recycling depend on the costs of collecting and sorting scrap, as well as the opening of wider markets to secondary materials.

20.5.6. Creating Voluntary Organizations and Agreements

Broad voluntary agreements have been fashioned between industry and government to curb energy demand. Such voluntary agreements free governments from the regulatory burden of setting up complicated and inefficient systems of industrial-equipment efficiency standards and operating norms, and enable industries to choose strategies and technologies that are most efficient from the point of view of industry-specific conditions and opportunities. However, the effectiveness of such arrangements clearly depends on the financial conditions facing the industry. When profit positions become less favorable, through internal or external circumstances, the incentive to honor voluntary agreements is likely to suffer.

20.5.7. Underwriting Demonstration Projects

Seeing is believing. Often, the amount of uncertainty associated with a new technology being applied to a new situation with untested goals and techniques is too great to convince managers to invest in it—even if theory indicates not only that the investment will be safe but also that it will return dividends throughout its lifetime. However, if those same managers see the technology successfully applied to a test bed under conditions that resemble their company's situation, they might be more convinced that it would work for them. Such demonstrations can be offered by government agencies, trade groups, developers of the technology, utilities, corporations, or other institutions. Cooperative efforts often are most effective.

20.5.8. Creating Legal and Institutional Instruments

20.5.8.1. Developing and Enforcing Standards

A final approach to reducing GHG emissions from the industrial sector is the development and imposition of standards. This strategy already has been used in such applications as automotive emissions and the energy efficiency of buildings. Such standards can be written by industry groups and incorporated into regulations or legislation. Such standards ensure that feasible goals are set, that the technology to achieve those goals is available or under development, that a level playing field is provided for all participants, that the information needed to comply with the standards is disseminated, and that monitoring and enforcement mechanisms are in place. One of the advantages of such an approach is its flexibility; the standards and the technologies they prescribe can change over time in response to technical advances, economic conditions, and the perception of social and political needs.

20.5.8.2. Expanding Land-Use Planning

Opportunities for efficiency improvement through system integration are substantial in densely populated areas of the industrial world, where sources of waste heat and materials and demands for low-temperature heat and waste materials as inputs often are located close together. Such opportunities, however, pose additional implementation barriers because the organizational and regulatory complexities of system-integration projects are particularly demanding. A positive attitude from local authorities and utility planners and an innovative approach in regional planning have proved essential in the few cases in which this approach has been successfully followed.

20.6. Conclusions

The worldwide industrial sector contributes a large percentage of GHGs to the atmosphere. The bulk of this is CO_2 associated with energy use, but significant quantities of process GHGs—including CO_2, CH_4, N_2O, CFCs, and other halo- and hydrohalocarbons—also are released. OECD industrial economies contribute the bulk of fossil fuel CO_2 emissions, but these have remained relatively constant over the past 2 decades. Transitional-economies emissions have declined sharply since 1988 with the contraction of economic output, while developing-economies emissions have grown as their industrial sectors have expanded. A number of opportunities have been identified in the most energy- and GHG-intensive industrial subsectors for more efficient use of energy and materials. Creating industrial ecosystems that make maximal use of recycled secondary materials as feedstocks and take advantage of cascaded lower-temperature heat can lead to substantial reductions in greenhouse gas releases. The use of low-carbon fuels, renewable energy technologies, less energy-intensive materials, and dematerialization can lead to lower GHG emissions in all economies. Shifting industrial practices to reduce GHG emissions (and other environmental pollutants) can occur as part of the regular replacement of capital stock, but information and a variety of economic incentives and other policies are likely to be needed to assure that replacement technologies and processes are chosen that lower GHG releases.

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